MACHINE-TOOL AUTOMATION BY ELECTRONIC CONTROL

(Automatic Repetitive Operation and Positioning by Tape, Computer and Other Related Methods)

MACHINERY'S
YELLOW BACK
—SERIES—
No. 38

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~~C. Crowther~~

Jno. Freeman.

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PREFACE

In the past, a fairly high degree of automatic operation of machine tools has been achieved by means of mechanical methods, notably by the application of cams. Also, some use has been made of arrangements incorporating limit switches, contactors, and methods whereby speed and feed rates were suitably changed by the manual operation of the tool turret. Recent developments in the perfection and utilisation of electronic devices have, however, led to refinements in servo-mechanisms and to the building of satisfactory electronic calculators. It is reasonable, therefore, that, in the general striving for greater production, the employment of these techniques to facilitate the operation and control of metal-cutting machines should not have been overlooked, but generally investigated.

As a consequence, a number of control systems have been devised, and have been described from time to time in Machinery's columns. Many of these are yet in the experimental stage, but their effect upon the ultimate automation of the industry, we believe, will be so important that it has been thought fit to bring the descriptions of these systems together in one book, for the convenience of those interested.

A number of the machines and systems described in this book are of American origin. Hence to facilitate those practically interested in obtaining further particulars, we give herewith a list of the American manufacturers concerned together with their British agents, as far as we can ascertain at the time of writing.

American Pacemaker Lathes...	Buck & Hickman, Ltd.
Cincinnati Milling Machines ...	Chas. Churchill & Co., Ltd.
Ex-Cell-O	Ex-Cell-O Corpn. (Machine Tools) Ltd.
Giddings & Lewis	Rockwell Machine Tool Co., Ltd.
Gisholt Machine Co.	Gaston E. Marbaix, Ltd.; and Burton, Griffiths & Co., Ltd.
Heald Machine Co.	Alfred Herbert, Ltd.
Monarch Machine Tool Co. ...	Rockwell Machine Tool Co., Ltd.

* * * * *

Attention is drawn to the fact that many of the devices and processes described and illustrated in this book are the subjects of valid patents at the time of writing, and many of the trade names mentioned are registered trade marks of certain manufacturers and traders, although individual mention may not have been made.

CONTENTS

CHAPTER 1

METHODS EMPLOYING MAGNETIC TAPE

For the production of many forms of components, machine tools can be designed to operate very satisfactorily on fully automatic cycles, when the various movements are controlled and co-ordinated by purely mechanical means. In other instances, designers have found it expedient to incorporate electrical, hydraulic or pneumatic systems, of varying degrees of complexity, in order to achieve the desired results. Sometimes, indeed, combinations of three or four systems may be adopted to solve particular problems. Thus, in view of the facilities and knowledge now available, and the ingenuity so often displayed by machine-tool designers, it is probable that almost any cycle of movements likely to be required, however intricate, could be effected automatically by what have come to be regarded as conventional means. Whereas this might well be possible in theory, however, automatic machines for certain purposes would tend, in practice, to become alarmingly intricate and prohibitively expensive. Moreover, set-up time for such a machine would be appreciable, so that the machine could only be used economically on long production runs.

In view of the growing demands of component designers for parts of increasing elaboration and accuracy, and the scarcity of skilled labour with the consequent need that it is employed to the best advantage, a demand exists for various general- and special-purpose machines which can be fairly rapidly set-up to function virtually without attention. It is desirable, moreover, that the equipment of such machines should not make excessive demands on the tool-room for the supply, for example, of templates, cams, and three-dimensional masters. What is required, in fact, is a substitute for the skilled operator which can control a comparatively simple machine through involved cycles, without waste of time, and without the errors that even a most competent man is liable to make from time to time.

Various investigations have been carried out with the object of solving this problem, and, in certain directions, considerable progress has been made. Particular interest has been shown in methods of control in which the operating cycle is effected by continuous scanning of a magnetic tape, and a number of these have been brought to an advanced stage of development. It is believed that this method will have considerable ultimate influence on the production systems of the future.

A single control unit can be employed to control the operation of two or more identical machines, when set-up for producing workpieces of the same form. Apart from tool changing, where necessary, all that

is required is the substitution of the appropriate magnetic tape, and some adjustment of the basic machine settings. It is possible for standard machines to retain their versatility, yet function for short or long runs automatically.

The magnetic tapes are compact and can be easily stored. They can also be readily duplicated, or modified by cutting and splicing. In one system, it has been stated, that with a 1-inch wide tape, as many as six continuous feeds or movements, and 35 intermittent, on-and-off functions can be automatically controlled, with a sound channel incorporated if necessary for giving oral instruction to the operator.

The foregoing has outlined the general necessity for greater automatic control for machine tools, and given some of the advantages of the employment of magnetic tape. It is now proposed to describe some of the systems so far devised.

G.E.C. System.* The use of magnetic tape to provide the signals necessary to control all the moving members of a machine tool throughout its operating cycle was first demonstrated by the General Electric Co., U.S.A., in 1947. The magnetic tape imparts a type of memory faculty to the machine tool, and the system has been called the "Record-Playback Control." The machine movements followed in making an initial work-piece are suitably recorded on the magnetic tape and then "played-back" when each subsequent duplicate workpiece is automatically machined. This system has been successfully applied to the control of a centre lathe and a milling machine.

Principle. While the initial workpiece is being machined, signals are obtained from Selsyns which are geared to the various members of the machine. A servo-mechanism operated electronically and incorporating amplidynes controls and drives the moving members in synchronization with the signals derived from the tape. In this way, smooth stepless reproduction of the recorded movements is obtained.

To adapt a machine to the system, each feed or movement is individually motorized and equipped with a Selsyn, and for each feed or movement a separate channel is required on the tape recorder. Other channels can be utilized for the purpose of switching auxiliary equipment on and off during the operating cycle. As many as five intermittent functions can be controlled by one recorder channel.

A machine that has been adapted to the system is the 16-in. American Pacemaker lathe shown in Fig. 2, the carriage and cross-slide feeds being individually motorized to permit of programming. Typical of the work performed on this lathe is the turning of stepped shafts.

A diagram representing the system is shown in Fig. 1. The coordinate feeds X and Y for either the work-table or tool-slide are motorized and incorporate Selsyns. Amplidynes supply an adjustable-voltage current to the motors. As shown in the diagram, the recorder has one channel for the feed X and another for the feed Y. It also has a third channel Z which energizes and de-energizes the motors for

*"Magnetic Tape Control of Machine Tools," L. R. Peaslee, *Machinery*, Vol. 84, page 483.

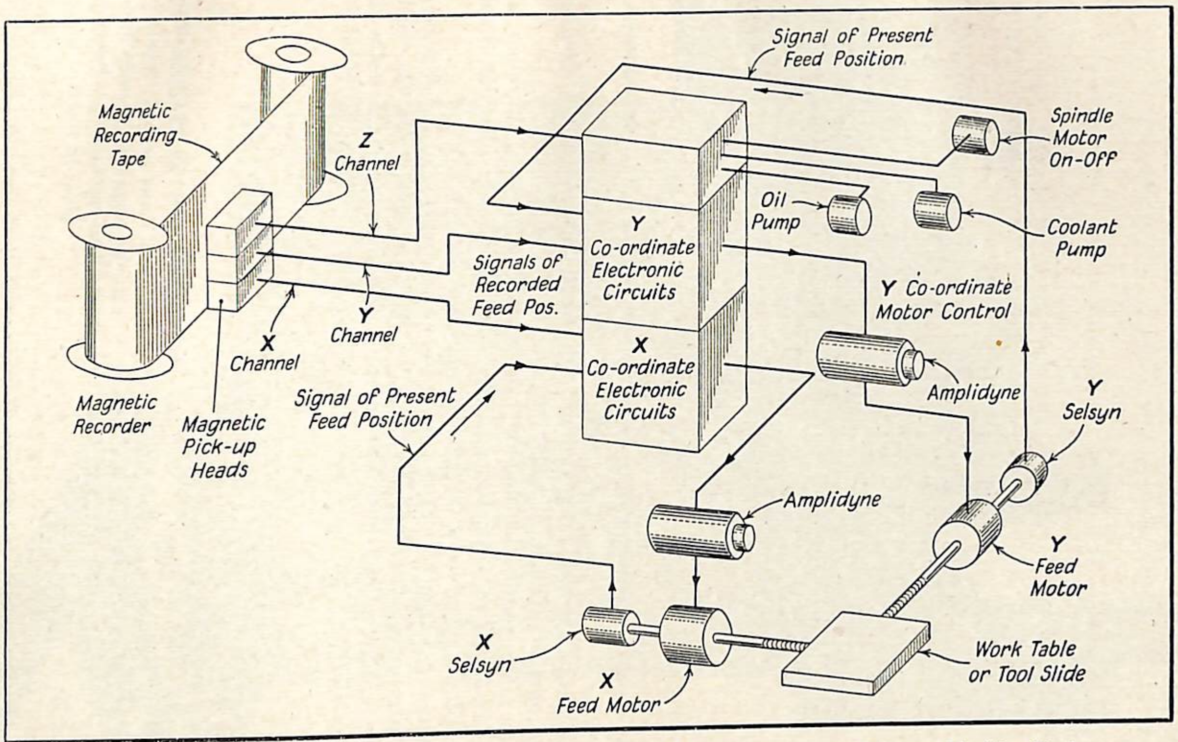

Fig. 1. Diagram showing a Typical Arrangement of the G.E.C. System as applied to a Machine Tool

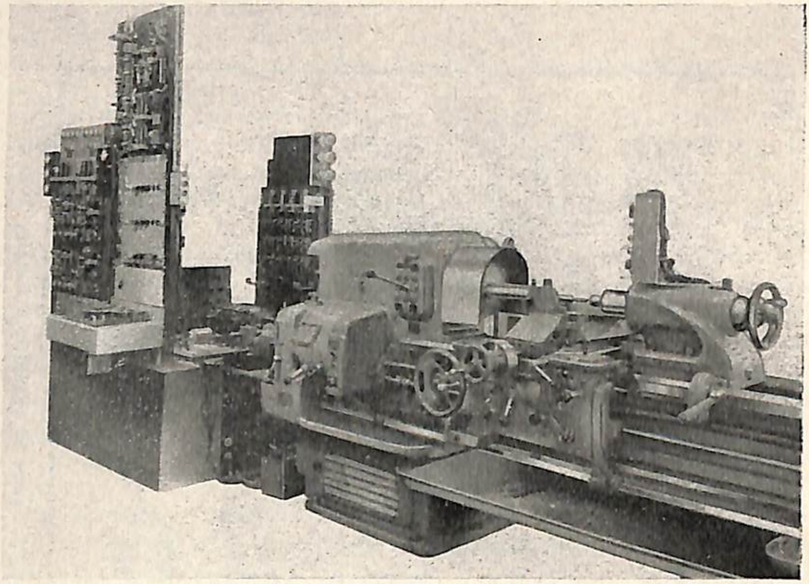

Fig. 2. American Pacemaker 16-in. Lathe equipped with the G.E.C. "Record-Playback Control"

the oil pump, the coolant pump and the spindle, at the correct moments in the operating cycle of the machine.

To programme the machine, it is only necessary to select the appropriate reel of magnetic tape, Fig. 3, place it in the recorder, set-up the workpiece and tool, and press the start button.

When the first end of the shaft has been rough- and finish-turned, the cutter automatically returns to the starting point, and the feeds, spindle and recorder automatically stop. The operator then turns the shaft end-for-end and presses the start button, whereupon the second

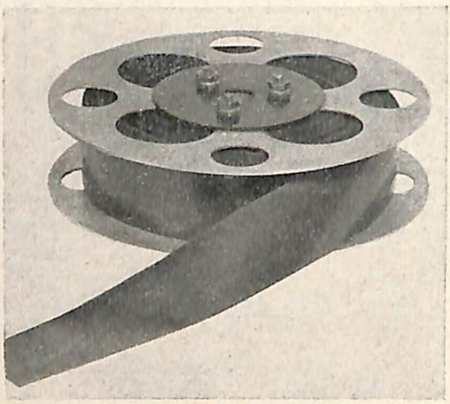

Fig. 3. Reel of Magnetic Tape on which the Control Signals are recorded and reproduced during the Working Cycle by Means of Pick-up Heads

end of the shaft is turned. As soon as all cuts have been taken, the recorder automatically stops the feeds and spindle, and starts rewinding back the magnetic tape. Before the operator can remove the finished workpiece and reload the chuck, the tape has been rewound to its starting point.

The magnetic tape for the shaft may be prepared by recording feed positions while the lathe is controlled by a hand-guided tracer. Other tape recordings have been made while the lathe was being operated under manual control.

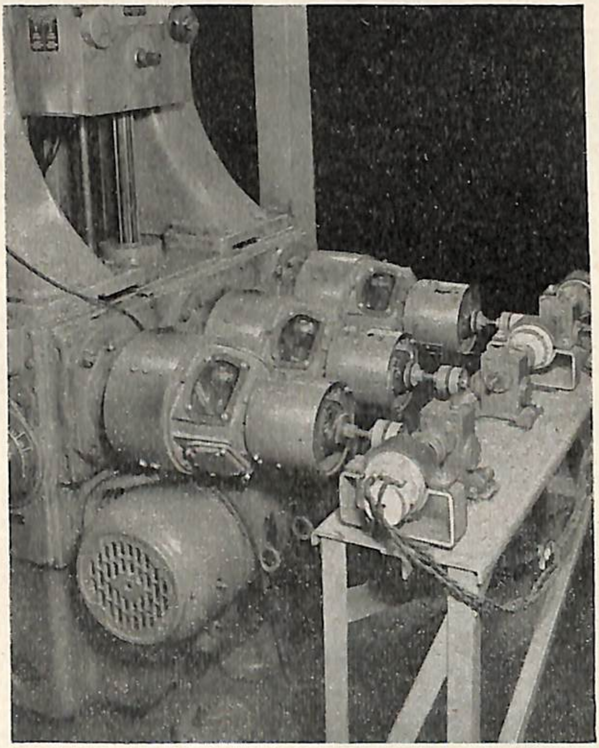

Fig. 4. The Feed Motors, Tachometers and Selsyns with which a Milling Machine adapted to the G.E.C. System is equipped

The same system has been applied to a Giddings & Lewis special milling machine located 50 ft. from the lathe already mentioned. A switch is provided for changing the control from one machine to the other. The three motors for driving the feeds of the milling machine are shown in Fig. 4. Selsyns are geared to tachometers which are coupled directly to the motors.

In Fig. 5 are shown some irregularly-shaped plates which were profiled to an accuracy of 0·001 in. on the milling machine. For the

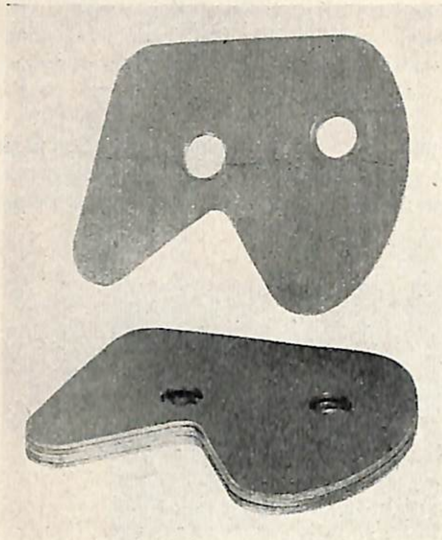

Fig. 5. Irregularly-shaped Plates with Contours that were profile-milled by a Machine controlled by the G.E.C. System

production of these, only the head and table feeds were required to be programmed by the system, the tape recording having been prepared while the machine was under the control of an automatic tracer. In another application, holes were produced in steel plates as shown in Fig. 6. For this, the accurate positioning of the boring tool from hole to hole was effected by a series of programmed movements, the recording having been prepared while the machine was manually controlled.

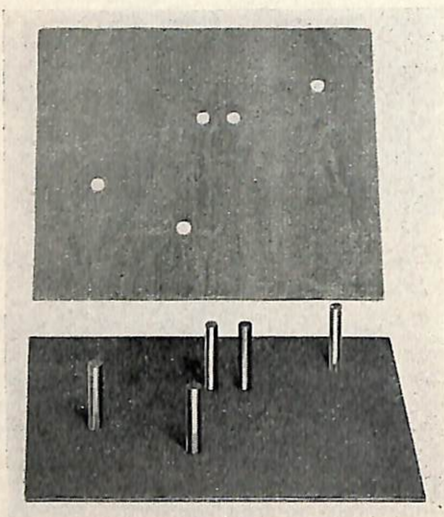

Fig. 6. The Holes in the Upper Plate, which were located and bored by Means of Automatic Control, accommodate the Pins of the Lower Plate

ADVANTAGES.—The G.E.C. system of "Record-Playback Control" is stated to permit a high degree of automatic operation of machine tools, enabling standard machines to retain their versatility yet able to compete with special machines on high-production runs. The system can direct complete operating or processing cycles, involving the co-ordination of virtually any number of motors, solenoids, relays, hydraulic valves, pneumatic valves, clutches, brakes, and other electrically-operated devices. For machine-tool applications, the control can automatically apply feeds, vary spindle speeds, index turrets, and turn coolant and oil pumps on and off, as well as operate clamping devices, loading devices, automatic chucks, and transfer mechanisms.

Small and medium-sized batches can be handled on a high-production basis, with substantial reductions in time. Little set-up time is required to change from one automatic cycle to a totally different cycle, and fewer tools are normally needed. It is unnecessary to adjust templates, or set limit switches or dogs. Inspection and measuring time are reduced or eliminated entirely. Furthermore, the possibility of errors by operators is eliminated.

The system is especially well adapted to cycles that are long and complicated, or require too many passes to permit the use of cams, templates or other mechanical devices for storing information. One milling operation which has been investigated would require 40 long templates to programme irregular shapes. In this instance, the system would reduce the floor-to-floor time by some 50 per cent, and such saving would result mainly from the elimination of the time required to change templates, make adjustments, and set limit switches.

Unusual operator skills that are difficult to reproduce on conventional automatic machines can be recorded on magnetic tape. Such skills are involved, for instance, in many assembly operations, although in most cases the appropriate machines must be first designed.

Two or more identical machines can be simultaneously controlled from one recorder. Where there are insufficient jobs on one type of machine to keep the "Record-Playback Control" fully occupied, the control may be alternated between two or more different types of machine, as in the previously mentioned applications to a lathe and a milling machine. The only requirement is that each machine must have individual motor-driven feeds.

Sometimes, it may be desirable to produce a workpiece of a size different from that of the workpiece from which the record was obtained. For example, the tape programme for machining a large ship's propeller could be recorded from a scale model, using a template follower. A different gear ratio would then be used on the "playback." It is also possible to arrange to obtain both right- and left-hand workpieces from the same tape recording.

A heavy-duty recorder is used for the tape, and as many as six continuous, or stepless, movements and 35 intermittent or "on-and-off" functions can be automatically controlled for a 30-minute programme from a standard $10\frac{1}{2}$-inch diameter reel of magnetic tape, 1-inch wide. A 14-inch reel will direct a 1-hour programme.

Where work loading is performed automatically, the time required for rewinding the tape at the end of each cycle is non-productive. In such cases, a special recorder using an endless loop of tape may be provided. Also, where more than six feeds or other functions are involved, tapes wider than 1-inch can be employed.

Tape recordings are generally made directly on the machine to be controlled, but where necessary, special equipment not connected with the machine may be used. Then, the initial operating cycle is performed by light moving members or in other ways which simulate the movements of the actual production machine. With either arrangement, the feed movements merely serve to drive the Selsyns from which the position signals are obtained. The various steps in making recordings are shown diagrammatically in Fig. 7.

Manual control of the machine is the simplest and most inexpensive method of making the recordings. The operator makes the workpiece on the machine while signals from the Selsyns geared to the feeds record all the movements of the machine. Usually, the movements are directed by means of the speed controls of the electronic and amplidyne drives, so as to ensure smoother and faster operation than is possible by the use of handwheels and geared feeds.

The non-productive time spent in taking trial cuts and measuring is eliminated by stopping the recorder during these operations. Still more time can be saved by setting clips on the feed micrometer dials, or by arranging indicators and gauge blocks to establish the various dimensions. Where the operating cycle is too fast to be recorded properly, it may be programmed at half speed or quarter speed, and then played back at normal speed.

If a tracer control is used to programme a machine while the Selsyn signals are being recorded, many advantages are obtained. Such tracer control represents only a small percentage of the total cost, and makes it possible to record smooth contours as well as straight lines, without having to stop for taking measurements, or to arrange special methods of measuring while a cut is in progress. This tracer control may be manual, with hand-guided stylus, or automatic.

When several passes are made over one template, the return to the starting point and the adjustment for the depth of cut for each pass can be made manually, or with the aid of limit switches. Should several passes with different contours be required, the recorder is shut down while the templates are changed, so that during play-back there is negligible delay.

If the size of the workpiece and template are such that there is insufficient space to accommodate both on the machine during programming, the workpiece need not be used. The tracing head and template then occupy the respective normal positions of cutter and workpiece, and the tape recording is made while the tracer control follows the template. For the "play-back" the tracing head and template are replaced by the cutter and workpiece.

The familiar tracer-control techniques may be applied in making tape recordings remote from the machine which is to be controlled.

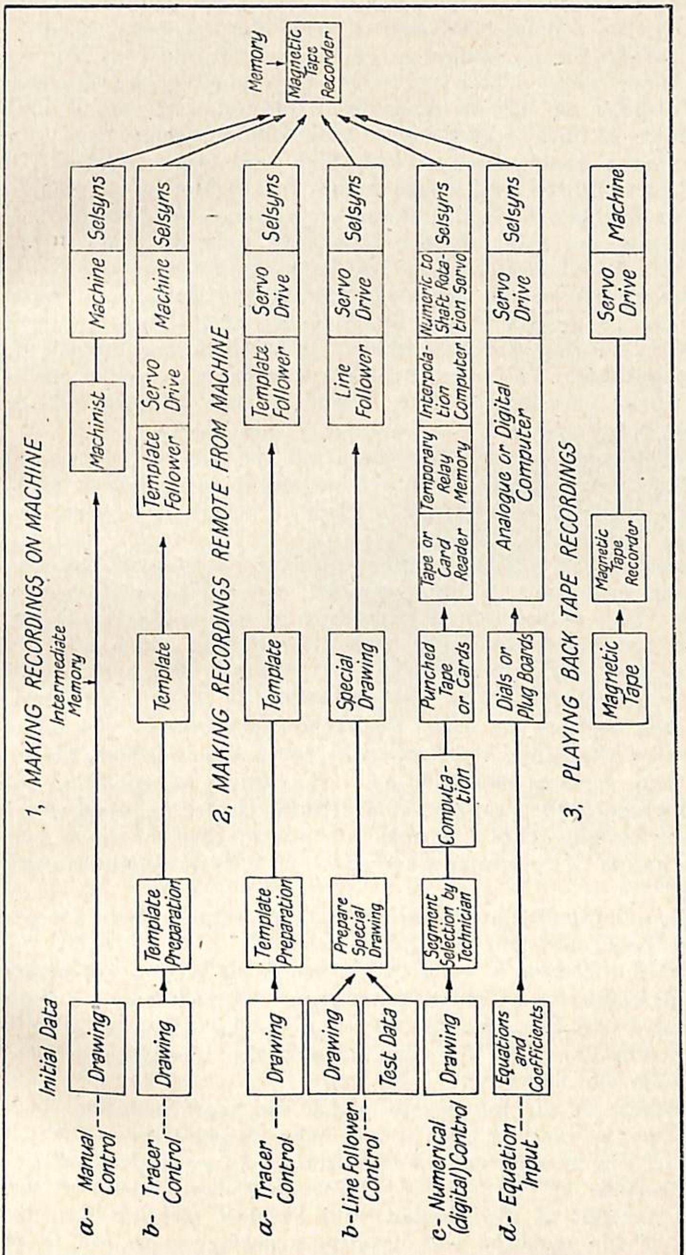

Fig. 7. Diagram indicating the Stages involved in the Various Methods of making the Recordings of the G.E.C. "Record-Playback Control"

A "mock-up" of the machine with the appropriate motor driven feeds to position the tracing head and to drive the Selsyns is used. Such versatile programming equipment will permit of preparing tape recordings for almost any machine tool having corresponding co-ordinate feeds.

Recordings can also be made from line followers, which duplicate the contours of lines on drawings. Line followers range from a simple type having a hand-guided stylus which turns the recording Selsyns directly, to completely automatic types. As in the case of the tracer-control recordings, the line follower programmes the Selsyns.

Drawings are generally less expensive to make than templates, but are also less accurate. This drawback can be overcome by making the drawings five or ten times the size of the workpieces, when the Selsyns can be geared to the line follower in the appropriate ratio. In this way, drawing errors are reduced to one-fifth or one-tenth of their actual magnitude. However, if the drawing size is excessive, recordings may be made successively from sections of the drawing. While the section is being changed, the recorder is inoperative.

Line followers are very suitable where the curves to be reproduced are initially developed or smoothed on the drawing board, as in the case of aircraft sections and turbine blades of which the curves are often developed from test data.

Numerical, or digital, machine programme controls can be used for making recordings, to eliminate the need for templates or special drawings. Key points along the contour of the workpiece to be programmed are represented by a series of numbers which are recorded in some form of digital "memory." For example, they may be punched into cards or tape which, in turn, is fed into a numerical control that programmes the Selsyns while the recording is made. To fill in the gaps between the points represented by successive numbers, the control requires some form of interpolation. Thus linear interpolation may be provided whereby the contours of the workpiece are made up of a series of straight-line segments. In order to obtain smooth curves between the data points, a computer to produce a cubic interpolation may be employed.

When numerical controls are applied, they are able to accept data that have been calculated on computers.

When the system is applied to such fields as process control, it may be desirable to record a programme derived from an equation having many variables, and the equation can be solved on a digital or analogue computer with a Selsyn output, the recording being made directly from the computer.

Regardless of the manner in which the tape recording has been prepared for the system, once it has been checked for correctness, it will produce the programme of operations whenever desired.

Applications of the "Record-Playback Control" system requires close co-operation of the machine-tool builder, since the mechanical condition of the machine will determine performance and accuracy. Back-lash, wind-up, cross-wind, and other lost motions should be kept to a minimum. When the control calls for a reversal of feed, the

moving member will hesitate until the backlash has been taken up, and subsequent over-shooting occurs as the feed rapidly tries to catch up with the control signals. For low feed rates, the resulting error is only a fraction of the amount of backlash, but at high feed rates the error may be equal to or greater than the amount of back-lash. At normal operating speeds, the control will compensate for a large part of the back-lash.

It has been found that static friction, running friction and inertia all affect performance, and stability circuits in the control are designed to minimize the influence of these factors.

The Selsyns, which measure distance, are generally geared to the feed-drive motors. To obtain a high degree of accuracy, or when playing back a recording made on another machine, the Selsyn should be driven from a precision rack attached to the carriage. In this way

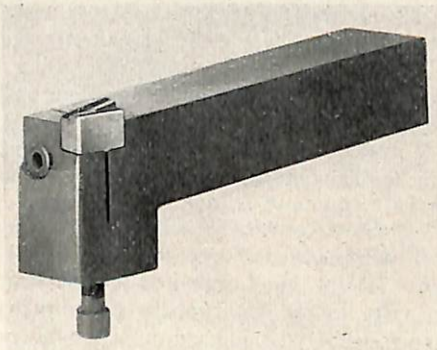

Fig. 8. A Type of Mechanically-held Tip which enables the Adjustment of the Tool itself to be avoided, when a Worn Cutting Edge is replaced

the Selsyns are isolated from the power gearing. Again, since leadscrews can usually be made more accurately than conventional racks, they may be substituted for racks if rigidly clamped to the machine.

The use of amplidynes renders the control versatile, in that it is adaptable to large machines requiring considerable power as well as to small machines on which fractional-horsepower motors are fitted.

In common with other automatic programme controls, the system requires that the cutter be accurately positioned with respect to the work during the set-up for the initial play-back. A control knob is provided to adjust each feed position, thereby permitting a rapid micrometer adjustment of the cutter with respect to the work. These adjustment knobs may also be used when the cutters are changed, and in some applications may be used to compensate for cutter wear.

For single-point tool operations, a tool having a mechanically-held tip, as seen in Fig. 8, often eliminates the need for making any adjustment for wear. The tip has four ground cutting edges; two on the top and two on the bottom.

It is usually possible to employ a few standard tools to cover a wide variety of jobs, so that special jigs can be provided to facilitate

tool adjustments. An alternative is to use tool assemblies which can be rapidly clamped against locating surfaces so as to ensure the correct cutter positions in relation to the workpieces. This enables all cutter adjustment and positioning to be done in the tool-room.

Giddings and Lewis Numericord System.* A control system based on the use of multi-channel magnetic tape has been made available commercially by the Giddings and Lewis Machine Tool Co., Fond du Lac, Wis., U.S.A. This is termed the Numericord system and is the result of contract research over some three years carried out at the Massachusetts Institute of Technology, and allied development work undertaken by the General Electric Co., Schenectady, N.Y. It provides for the preparation of magnetic tapes from numerical data, and for the application of such tapes to the completely automatic control of heavy-duty machines capable of handling large complicated workpieces.

With the Numericord system, operation cycles involving as many as five main machine movements, and twenty-two auxiliary functions may be controlled. The main movements may comprise, for example, traverse of the machine table in two directions along the two principal axes in the horizontal plane; traverse of one cutter-head in two directions, transversely and vertically.

The system can be applied to practically any machine tool, and one application demonstrated has been in connection with the large aircraft spar and skin milling machine shown in Fig. 9. This machine is capable of removing 450 cu. ins. of metal per minute, and is equipped with a rise-and-fall type cutter head, of 100 h.p., as seen to the right, and a 50-h.p. head arranged for 360-deg. profiling operations, at the left.

The heads incorporate mist-lubricated bearings, and the normal cutter speed is 3,600 r.p.m. A table with a work area 14 ft. long by 6 ft. wide is provided, and the maximum distance under the cross-rail of the machine is 4 ft.

Under Numericord control, the machine is capable of performing all the plunge, channel, pocket, and contouring cuts necessary to mill the integrally-stiffened skin and wing panels for modern aircraft from solid 75 ST aluminium plate. It is claimed that savings of at least 50 per cent can be effected in machining time, as compared with manually-controlled cutting operations, and that the simultaneous control of feed movements in several directions, and the very substantial reductions effected in non-cutting times, have resulted in very high machine utilization. Losses in time and material resulting from wasted operator motions, miscalculations and human errors are avoided, and the inaccuracies which may be encountered in tracer-controlled machines, and the problems associated with the mounting of templates and the design of mechanical linkages for multi-template profiling operations, are eliminated. Since machining accuracy is governed by the engineering planning at the tape preparation stage, and is independent of operator skill, highly-trained operators may be released for other duties, and replaced by semi-skilled labour.

**Machinery*, Vol. 87, page 151.

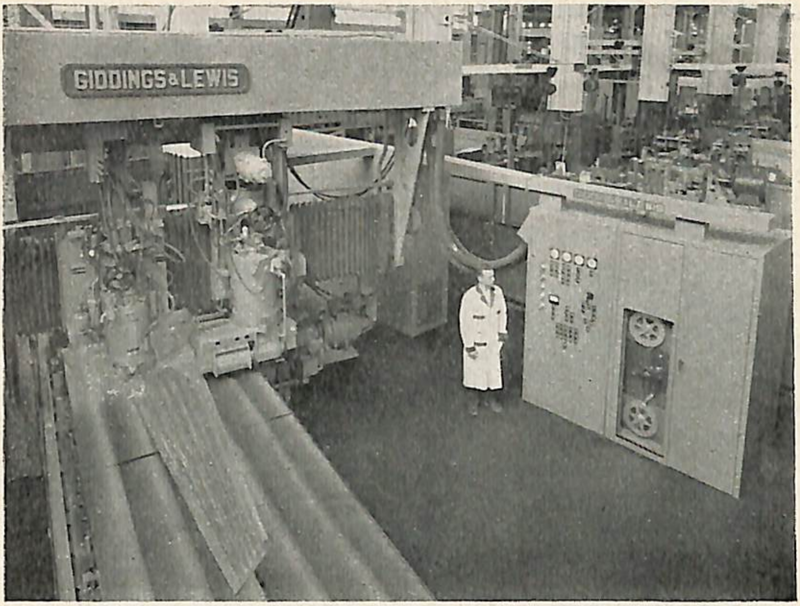

Fig. 9. General View of a Giddings & Lewis Skin and Spar Milling Machine controlled by the Numericord System. The Machine Play-back Unit may be seen at the Right

With the Numericord system, tapes can be prepared on a continuous production basis for all the machines in a given shop, and files of tapes can be maintained to permit rapid changeover from the production of one component to another. Modifications in component design can be incorporated in the tapes and put into effect at a later date. Tapes may be transferred from one machine to another, and from plant to plant, and can be prepared in advance and stored to meet emergency demands for increased output.

Preparation of the Tape. The sequence of operations in the preparation and application of the control tape starts with the transfer of pre-calculated data, in normal decimal form, from drawings, tooling studies and machine-tool feed charts, to the proper tape unit. Here a paper tape is prepared, and fed into the computing director where it is converted into time-based continuous electrical signals. An associated tape recorder transfers these signals to the appropriate channels of a master magnetic tape. This tape is passed through a playback and machine-control unit adjacent to the machine, which, by the means of servo-mechanisms, controls the main movements and auxiliary functions of the machine tool.

A general view of the tape-preparation equipment is shown in Fig. 10. This equipment is remote from the machine shops, and may serve almost any number of machines. Tape preparation is simple,

versatile, and is stated to be practically foolproof. Information in decimal numerical form concerned, for example, with movements along the machine axes and the related intervals of time, is transcribed by the operator from data supplied by the production engineers to paper tape, by means of a 16-key electrical control board at the desk seen in the foreground. Special instructions are incorporated in the tape by using six auxiliary keys. For checking purposes, a visual copy of all the transcribed data is prepared simultaneously by an electric typewriter.

Fig. 10. The Desk-type Unit used for transferring Data from Drawings and Planning Sheets to Perforated Paper Tape. The Magnetic Tape is prepared on the Equipment seen in the Background

Electronic circuits housed within the desk verify all the data that are fed into the equipment, and indicate such errors as the omission of plus or minus signs from the movement instructions, use of feed or distance data that exceed previously established values, and the specification of wrong numbers of digits or the incorrect final figure of any instruction. Supervisory circuits in the desk unit examine all data used in the preparation of the paper tape, and additional holes are perforated, where necessary, to ensure logical control of the electronic computing director seen in the background.

In the preparation of the tape, the operator may incorporate "stop" codes to provide intervals for tool replacement and for checking the machine and tool settings. By this arrangement, should a machining

sequence be interrupted by the breakage of a tool, it is only necessary to return to the previous "stop" signal, insert a fresh tool and restart the cycle. Automatic control resumes at that "stop" point and continues to the end of the machining sequence unless similarly interrupted.

The equipment housed in the desk for paper-tape preparation may be readily observed from Fig. 11. On top of the desk is the operator's keyboard and the electric typewriter. In front of the latter is the tape-perforating mechanism, the paper being fed from spools in the cupboard

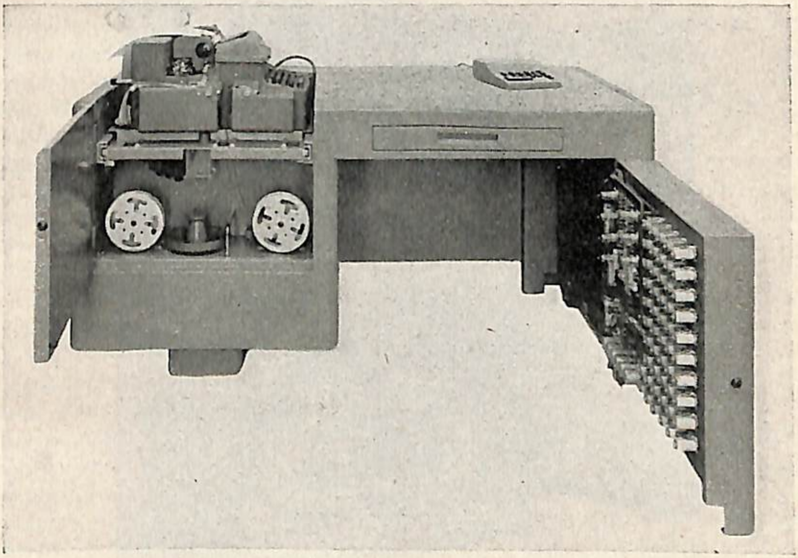

Fig. 11. The Desk for the Preparation of the Paper Tape houses Electronic Checking Equipment, the Perforating Mechanism and an Electric Typewriter which makes a typed Copy of the punched Information

below. Swung outwards from under the leg-well is the electronic-valve and relay bank by which the data fed into the unit are controlled and checked. The desk unit is completely independent of the computing director and has its own integral power pack.

To facilitate the calculation of machine movements and time co-ordinates, tool feeds and traverses, and other data necessary for the preparation of the paper tape, standard engineering type computers can be employed, and these require only the addition of tape-punching units in the output circuits to adapt them for the preparation of Numericord paper tapes.

Preparation of the Magnetic Tape.—The decimal digital information punched into the paper tape is converted into phase-modulated continuous electrical signals for recording on to a multi-channel magnetic tape by the electronic computing director. In this

equipment, the punched tape is scanned line-by-line and the information presented is stored in special magnetic-core memory units until the computing director releases it to secondary memory units, or directly to the data-co-ordinating units for final recording on magnetic tapes, as may be required by the machining programme. While one group of instructions is being processed, the following groups are being scanned

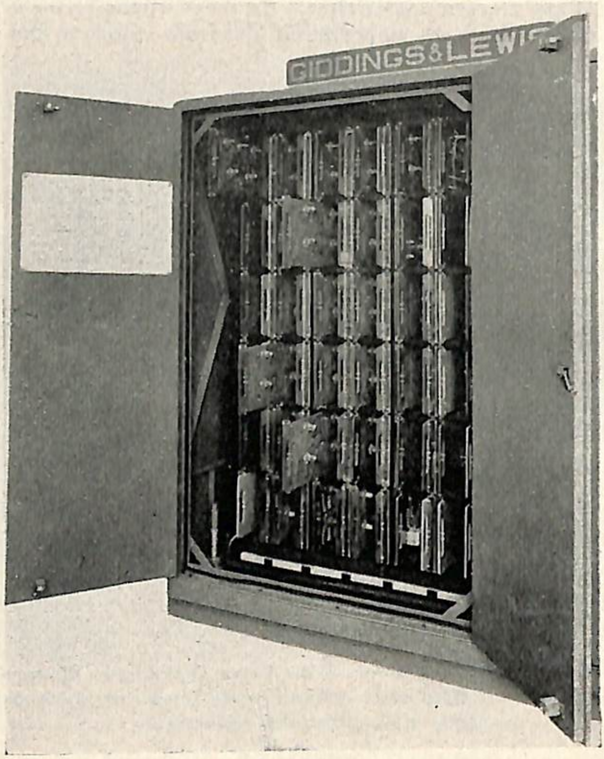

Fig. 12. Printed Circuits are widely employed in the Numericord System, the Circuits being on Boards that slide in Racks to facilitate Inspection and Maintenance

to ensure that the motions of the associated metal-working machine are continuous when the finished tape is played back.

The scanning of the paper tape is completely automatic, and visual indicators are incorporated on the control panel of the computing director to provide one fine and five coarse repeaters, which algebraically sum up all the distance "commands" for each of the principal motions of the machine tool, as the programme proceeds. The various motions are shown graphically on the panel, and, by means of a push-button, the fine repeater can be coupled to any of the coarse repeaters, so that the position of any tool may be precisely checked at any time by the super-

visor of the computing director, as if he were directly controlling the machine tool. At the lower left on the control panel is a signal window which is illuminated to read "trouble" should any circuit not be functioning properly.

The power supply equipment for the computing director is housed in a separate cabinet at the left of Fig. 10, and the magnetic-tape recorder at the right. The latter unit can be used to check the magnetic tapes. An important feature of the Numericord system is the use of standard commercial electronic and electrical components of established reliability. Most of the electronic components incorporated in the computing director, the magnetic-tape recorder and the play-back unit are of the printed type to provide a long service life, and to reduce maintenance. These circuits take the form of removable boards with rear plug-in contacts, and several such boards may be seen in Fig. 12, projecting from the racks in which they slide. More than 90 circuit boards are employed in the complete Numericord system in order to facilitate inspection and maintenance. All the electronic valves are of computer quality, and operate well below their maximum rating. The relays used throughout the system are of telephone quality, with bifurcated contacts. Most of the circuits are arranged so that they are "safe" in the event of failure. Both the computer director and the machine control cabinets have under- and over-voltage protection, and an integral ventilating system supplies filtered air to maintain all the circuits and components at the optimum operating temperature.

Application of Tape to Machine Control. The machine play-back unit may be seen at the right of Fig. 9, and at the rear of Fig. 13. In this unit, the magnetic tape is read electronically, and the resulting signals are employed to control minute-current-response, wide-range, amplidyne servo-mechanisms driving each of the feed and traverse motions of the associated machine tool. The accuracy of the machining operation is governed by the accuracy of the machine, and it is stated that tolerances ranging from plus and minus 0·001 to plus and minus 0·002 in. can usually be maintained. All 14 channels of the magnetic tape are read simultaneously, and, in addition to the signals necessary to control the principal machine movements, other signals may be incorporated for auxiliary functions, non-feeding controls and "spoken" commands. The latter may be employed to indicate to the machine attendant that the time for a tool change is imminent, for example, or that the machine is about to make a planned stop for inspection purposes. The auxiliary channels may be employed for such purposes as transferring the drive from the left- to the right-hand head, controlling the flow of coolant, engaging chip conveyors, and operating oil pumps.

Power for each main motion of the machine tool is derived from d.c. motors, and is transmitted through ball-bearing nut and screw mechanisms. Each motion has its own closed-loop feed-back servo-circuit, precision racks and pinions, mounted parallel to the direction of motion, translating the feed motion into rotary movements of the shafts of the synchro-motors. A movement of 0·1 in. of a machine member, such as a table or a cutter head, produces one complete revolution of the

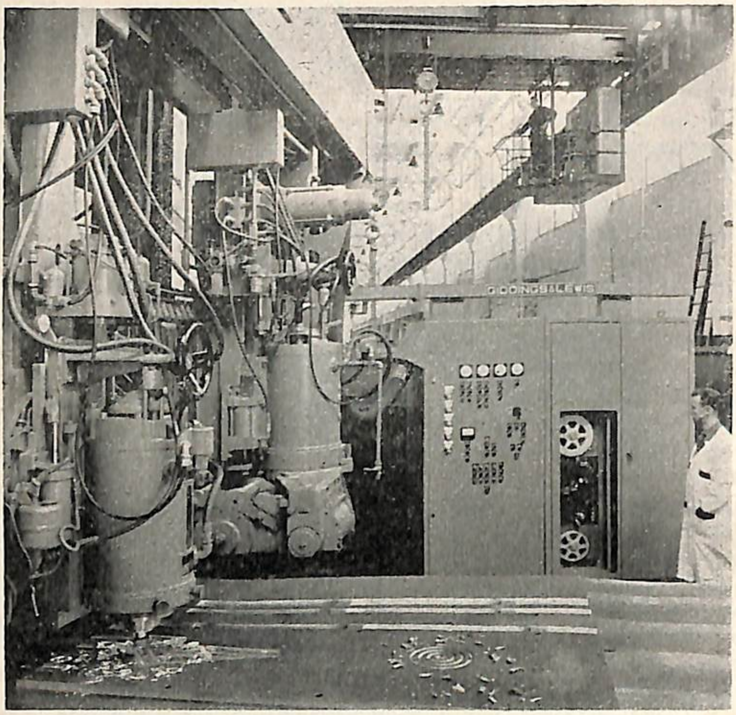

Fig. 13. A Demonstration of the Numericord System by machining an Archimedian Spiral from Data prepared on an I.B.M. Computer

synchro-motor rotor shaft. Both the driving and the feed-back mechanisms are designed to ensure minimum backlash and freedom from friction, so that the positioning movements can be performed to the maximum degree of accuracy and the machining operations carried out to high standards of surface finish.

In addition to the procedure outlined, the Giddings and Lewis Numericord system may be employed in a number of different ways. The machine control section of the system can be employed to produce its own tapes, independent of the computer director. Tapes may thus be prepared by operating the machine under template control, signals then being fed back to the control unit by the synchro-motors and recorded on tape. When the entire machining programme has been recorded, the machine may be employed to produce successive workpieces solely under tape control. Alternatively, the machine may put through the motions necessary to produce a given workpiece, and the movements of the machine members recorded, with non-cutting intervals of more than 20 secs. duration automatically omitted. In this way, a recording can be made which provides a virtually continuous machining cycle when played back. Another method that may be adopted is to

employ a skilled operator to machine the first workpiece of the batch, and to use a recording of the machine movements, made under his skilled control, for the production of the remaining components.

During a demonstration of the Numericord system, the skin-milling machine was employed to machine an Archimedian spiral of 8 ins. major diameter, in aluminium plate. The finished spiral may be seen to the right in the foreground of Fig. 13. The necessary co-ordinate data for the production of this spiral was prepared in the I.B.M. computing equipment of the Giddings and Lewis plant.

In addition to its application to the spar and skin milling machine, as already described, the system may be employed to control horizontal boring, drilling and milling machines, plano-milling machines and vertical boring mills. However, since the system provides for the control of five principal machine motions simultaneously, it is considered that it can be most effectively applied to variable axis, 3-dimensional contouring machines, such as the Variax range of the same Company for the machining operations on complex airframe components.

Automatic Turret-lathe Operation by the Gisholt System.*—The automatic operation of machine tools by the application of magnetic tape records has also been investigated by the Gisholt Machine Co., U.S.A. According to the findings of this company, most of the major problems of tape control for machine tools have been concerned with practicability. Thus the system must meet the basic requirements common to any form of machine-tool control, and be as simple and as compact as possible. Maintenance must be reasonably inexpensive and easy, and the system must be so designed as to permit of operation by unskilled employees. Also the control must be economically practical, both as regards initial and operating costs.

The Gisholt Machine Co., in carrying out an extensive development programme on the operation of machine tools from stored information, have, it is believed, produced a tape control for a turret lathe which comes close to fulfilling these requirements. The system comprises, essentially, an analogue computer used in a closed-loop system to provide a completely automatic machine cycle.

The basic elements of the system are a multi-track magnetic tape; detector screws for each track; an amplifier and shaper for all but one of the detectors, and a control panel for that detector; a reference meter bar and its associated detector screw; and, finally, a phase-sensitive detector and a hydraulic servo-valve.

The stainless-steel magnetic tape used can store information on several tracks, but for the purposes of explanation, it will be considered to have only three—an auxiliary track, a primary signal track, and a reference track. The auxiliary control track consists of a series of parallel lines for all step functions, such as spindle-speed changing or indexing. Parallel magnetic lines are recorded on this track, and when

*"Automatic Turret Lathe Controlled by Magnetic Tape," by L. Hesse, *Machinery*, Vol. 87, page 1302.

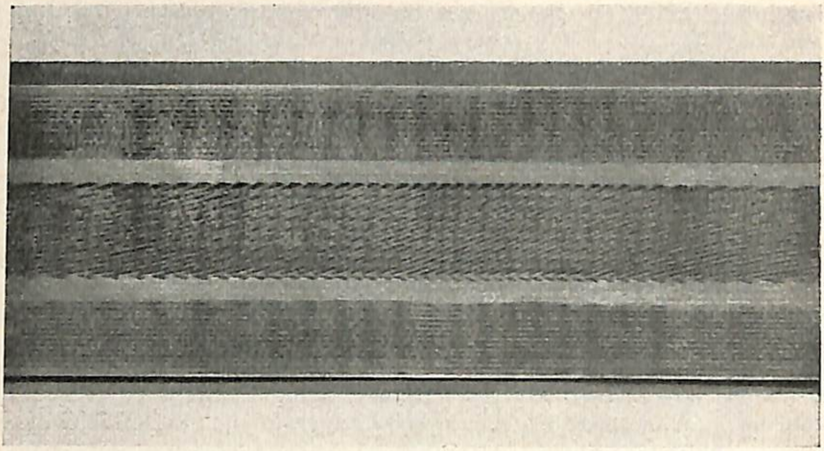

Fig. 14. Portion of a Stainless-steel Magnetic Tape which has been treated to show the Auxiliary Control Track at the Top, the Primary Signal Track at the Centre, and the Reference Track at the Bottom

it is required to give a signal, the lines are shifted laterally. The screw pick-up reads this lateral shift, and each 90-deg. phase shift will supply to a counting circuit, information calling for the performance of an auxiliary step function.

The lines on the primary signal track may be parallel to the edge of the tape, or may slant to the right or the left. This track determines the direction and speed of the machine carriage. If the tape speed is held constant, the rate of carriage movement is a function of the displacement angle of the primary signal traces. The reference track, which supplies the reference signal, consists of a series of parallel lines which are recorded on the tape at the same time as the primary signal information.

To enable these tracks to be seen for the purposes of Fig. 14, a section of the control tape was dipped in a bath of lacquer thinner containing finely-divided particles of iron in suspension. It will be seen that the upper, auxiliary, track does not include a phase-shift signal. The centre, or primary, track clearly indicates the manner in which the traces slope to provide a variable frequency for carriage movement control. It is thus possible to exercise complete control over acceleration and deceleration during any part of the carriage movement. The lower, or reference, track is merely a series of parallel straight lines. The number of lines on any track is not critical, the primary requirement being to generate a signal amplitude which is large enough to result in an adequate signal-to-noise ratio. With the tape shown, the signal-to-noise ratio is approximately 230 to 1, and the pick-up output voltage is approximately 0.100 r.m.s.

The tracks on the tape are continuously scanned by three screws, all mounted on the shaft of a 60-cycle synchronous motor which rotates

at 3,600 r.p.m. Each screw has a two-start thread with a pitch equal to the distance between the traces or lines of its respective track. As the screws revolve, the pick-ups associated with them supply control signals to the system. These signals take the form of sinusoidal voltages having a frequency of 120 cycles per second.

The signal which is picked up from the reference track is fed to the power amplifier which drives a synchronous motor connected, by means of a flexible shaft, to another screw. This screw picks up signals which have been recorded on a steel meter ribbon. The magnetic impressions causing these signals consist of "pips" which have been accurately located on the ribbon and spaced to correspond to the threads of the two-start screw employed. When the carriage is stationary, the pick-up associated with this screw generates a frequency of 120 cycles per second. This unit, known as the secondary generator, performs two functions: it provides a feed-back signal for the servo-loop; and allows automatic compensation for any tape shift during play-back.

As mentioned, the traces of the primary signal track may be either parallel or may be inclined to the right or the left. If the tape is stationary, the primary signal pick-up will always generate a voltage of 120 cycles per second, regardless of the slope of the lines on the track. If the tape is moving at a constant rate, however, the frequency of

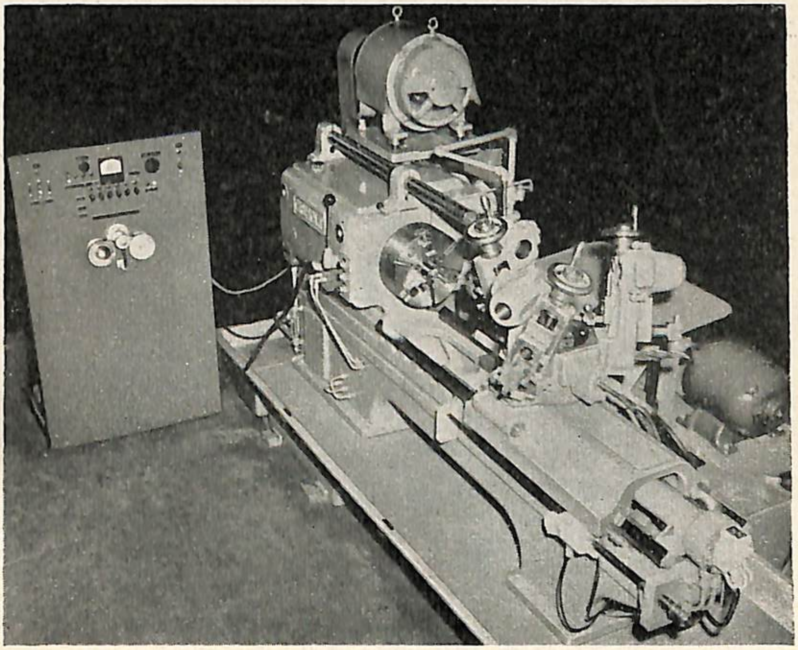

Fig. 15. Gisholt Fastermatic Automatic Turret Lathe set-up with the System for Over-all Control

the voltage will change in proportion to the slope of the lines. Depending upon the direction in which the screw is rotating, the frequency will be more or less than the base frequency, depending on whether the lines are inclined to the right or the left. Since scanning is continuous, this frequency change is interpreted by the system as a phase shift.

A signal from the primary track is fed into a phase-sensitive detector, and the signal from the secondary generator is fed into the same detector. This detector senses the instantaneous error signal and actuates the servo valve to correct for it. The signals which are being picked up are all shaped and squared before they are fed into the phase-sensitive detector. In consequence, the circuits are not amplitude conscious.

An experimental set-up of the over-all control applied to a Gisholt Fastermatic automatic turret lathe is illustrated in Fig. 15. The controls seen at the left were panel-mounted to provide convenience for adjustment, testing, and analysis. Parts of the control system which are attached to the lathe consist of a servo valve (seen at the lower right on the end of the longitudinal cylinder), and a secondary generator operating in conjunction with a meter ribbon. The meter ribbon is attached to the lathe bed, and the secondary generator is attached to and moves with the carriage, which is the controlled element.

A close-up view of the experimental panel is shown in Fig. 16.

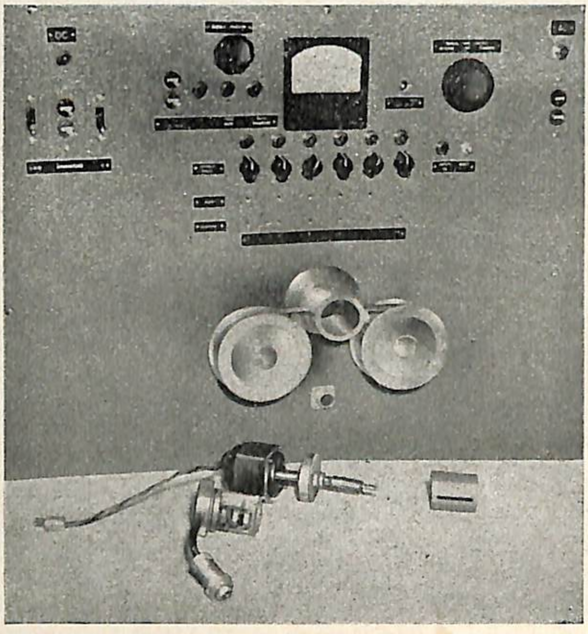

Fig. 16. Experimental Control Panel employed in conjunction with a Servo Valve, a Secondary Generator and a Meter Ribbon for Automatic Operation of the Turret Lathe

The controls on the extreme right and left are for the power supplies. Near the top centre is a meter which indicates the feed rate of the turret in inches per minute. The knob to the left of the meter is used to adjust the phase-angle to bring the system to zero. To the right of the meter is a manual tape-drive control to provide either manual forward or reverse of the tape-drive motor. Immediately below the feed-rate meter is a row of lights to indicate which turret face is in the operating position at any part of the cycle. Below the indicator lights is a row of switch knobs which enable the desired spindle speeds for the various turrets to be preselected.

Since the frequency of the signal produced by the primary signal generator is also a function of the speed of the tape drive, it is possible to have some control over the feed rates for the individual turret faces. Below the row of spindle-speed selector switches is a row of holes giving access to a group of potentiometers. These provide a means of controlling the tape-drive speed, within limits, for each turret face. It is therefore unnecessary to make a new tape if the recorded feed rates require minor changes in connection with the operation of the tools or any on all of the turret faces.

Below the feed-control potentiometers is another row of potentiometers, which permit control, within limits, of the actual position of the carriage with respect to the information picked up by the primary signal generator. This provision makes minor adjustments to tools to compensate for tool wear unnecessary.

The tape-drive mechanism is seen at the bottom centre of the panel. This accurately controlled, variable-speed drive provides for tape movement and rewinding. For traverse rates, the speed of the tape is increased as required. The feed-control potentiometers are employed in this adjustable-speed drive circuit so that the feed-rate adjustments are actually changes in tape-drive speed.

To conserve tape, the maximum displacement angle of primary signal traces is usually employed. Since the maximum angle has a tangent of 0·5, 30ft. of tape will give a displacement of 15ft. when the pitches of the meter ribbon and the control-tape are equal.

Another factor in a system of this kind is the technique adopted for storing the desired information on the tape. In a stored-information scheme, the cost of tape processing may make the difference between a control system which can be used only on parts required in large quantities, and one which can be universally applied.

The recorder for the Gisholt system is housed in a small cabinet, Fig. 17, with the associated electronic equipment in the base. This particular mechanism was designed to record simultaneously two primary signal tracks, and there is also provision for auxiliary control information. The result is a two-dimensional control with a versatility as good as, or better than that which could be obtained with a conventional two-dimensional tracer. One of the primary signal tracks would control the movement on the *XX*-axis, while the other would control the motion of the tool on the *YY*-axis. The resulting tool motion is thus a combination of both movements.

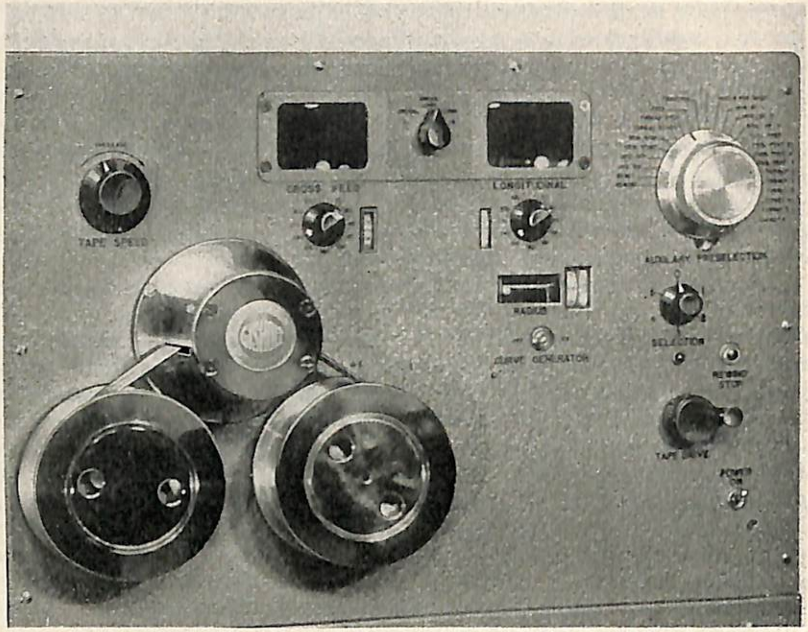

Fig. 17. Mechanism housed in the Cabinet simultaneously records Two Primary Signal Tracks and the Auxiliary Data for the Two-dimensional Automatic Control

The tape-drive mechanism, seen at the left, moves the tape past the recording head during the recording process. A four-position selector switch provides a means of selecting the information to be recorded. By means of this switch, the information being fed into the mechanism can be recorded on the XX-axis, zero, the YY-axis, or on both the XX- and YY-axes. Behind each window at the top of the panel are electronic devices which will measure to within 0·001 in. the amount of carriage movement being recorded.

Two controls are provided to indicate the direction in which the co-ordinates of the final tool movement are to be fed into the system. These dials have markings to indicate angles from 0 to 180 deg. in either direction. Thus when a tape is being made, a chamfer can be recorded by setting this knob to the correct direction and angle. A radius control switches an integrator into the circuit, so that curves, radii and fillets can be automatically recorded.

At the upper right of the panel is a 40-position auxiliary pre-selector. This is used to record the necessary degrees of electrical phase shift on the auxiliary track so that the necessary auxiliary functions are performed at the times desired.

The knob on the upper left of the cabinet is used to provide coarse control of the tape drive during recording. When the desired final dimension is approached (as read on the electronic measuring devices),

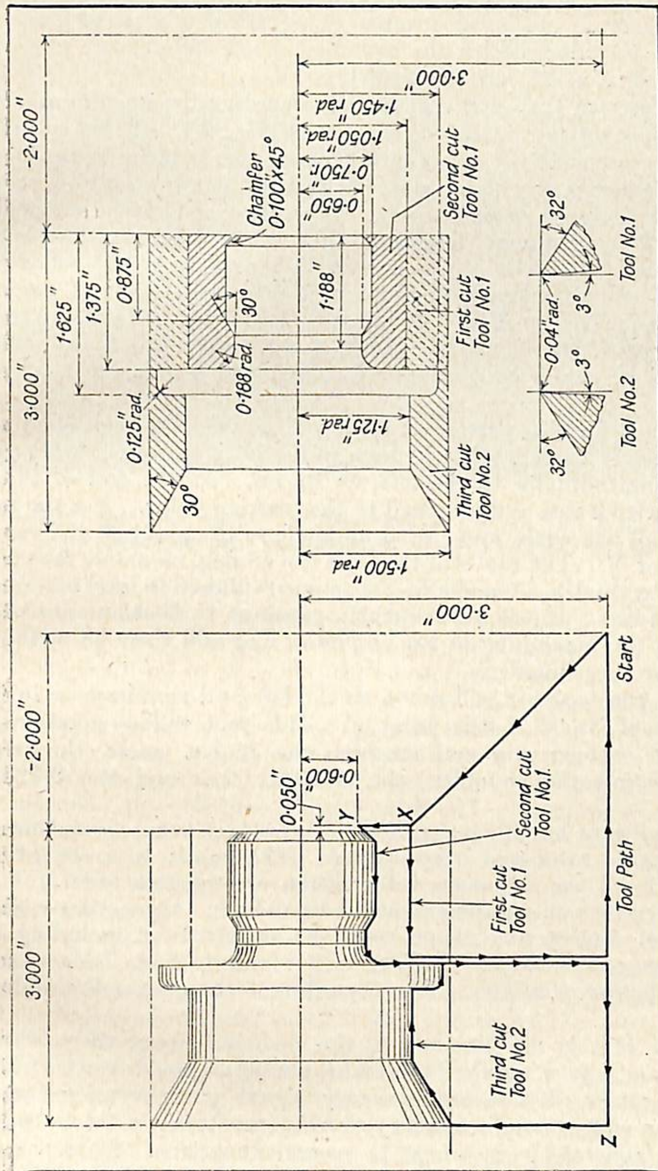

Fig. 18. Hypothetical Workpiece showing the Stages of Machining under Automatic Control

the final increments of distance are fed into the unit by means of the hand crank seen at the lower right of the panel. The distances recorded are the result of the total number of electrical degrees of phase shift which are introduced into the system. Each 360-deg. of phase shift represents 0·1 in. of carriage travel.

To illustrate the operation of this recording device, the machining of the hypothetical workpiece shown in Fig. 18 will be considered. Only the cross-slide of a standard Gisholt turret lathe is to be used. The particular part shown was selected to draw attention to some interesting features of the system. The piece has been dimensioned so that all longitudinal dimensions are taken from its end, and all measurements at right angles to the *YY*-axis from the centre line. Cut No. 1 will be taken with tool No. 1 to remove some of the excess stock, and cut No. 2 will also be taken by tool No. 1 to form the contour at the right of the shoulder. Next, the toolpost will index, and cut No. 3 will be taken by tool No. 2, which will be traversed from left to right.

The tool for this particular piece will be initially positioned at the point marked "start". It will then move in at an angle to the point *X*, and longitudinally to the left, as shown. At the end of this cut, it will be withdrawn and returned to the starting point. For the second cut, the tool will again move in at an angle to the point *X* and continue to the point *Y*. The tool will then cut the 45-deg. chamfer, the straight portion, the 30-deg. chamfer in the opposite direction, the flat surface, and the radius. It will subsequently continue to feed out until it has completed the machining of the shoulder, and will then be withdrawn away from the shoulder.

Next, the toolpost will move to the left and simultaneously index to bring tool No. 2 to the point *Z*. This tool will now traverse in, slow down to feed rate and machine the 30-deg. angle, the straight portion behind the shoulder, the shoulder face and the 0·126-inch radius.

To facilitate handling the information which must be fed into the recorder, it is tabulated step-by-step. The result is a set of work sheets with all the necessary information arranged in order.

Other analogue equipment could be used in conjunction with this device, and almost any shape could be recorded by including more steps. Traverse rates up to 350 ins. per minute have been obtained with satisfactory stability. The recording techniques are simple and rapid.

In the further development of the Gisholt system, there seems to be no reason why a number of auxiliary tracks should not be utilized, nor any reason why several primary signal generators, operating in conjunction with several secondary signal generators, should not be used to provide controlled movement in several directions. Since a control signal is generated regardless of whether the tape is moving or stationary, it would also be possible to use this system to correlate a group of discontinuous functions in several directions which might be either on the same machine or on different units.

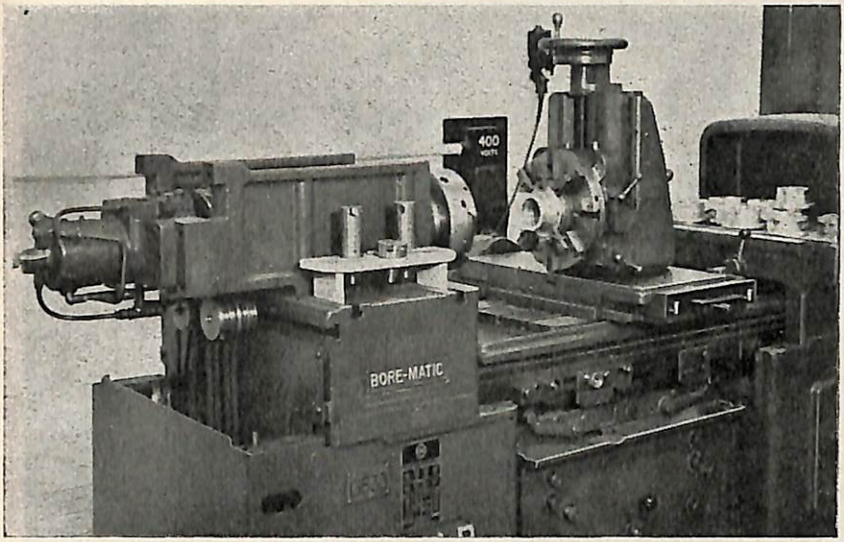

Fig. 19. Heald Borematic operated by Magnetic-tape Control. Three Working Cycles are obtained on what was previously a Single-purpose Machine

Alfred Herbert System.* A system of machine control which is based on the selectivity of sonically tuned relays has been developed and applied by the Factored Division of Alfred Herbert Ltd., Coventry. This sytem is stated to have certain advantages over those employing synchros or computers. When synchros are employed, each machine slide or moving member requires a separate track on the magnetic tape, and where the reduction of machine functions to coded data is carried out by digital computers in a series of pulses for purposes of recording, it is contended that the loss of one pulse out of perhaps hundreds of thousands may tend to produce inaccuracies in the workpiece. In the Herbert system the risk of losing a signal is said to have been eliminated. It is pointed out that the tape recorder was originally developed to record faithfully such complex combination of frequencies as occur, for example when a large orchestra is playing, all of which frequencies are intermingled on the one track. It was therefore decided to exploit these principles, and to convert machine movements into frequencies which would be heard as musical tones if the output of the recorder were applied to a loud speaker.

Equipment embodying these principles has been applied to a Heald Borematic, Fig. 19, using a standard commercial recorder unit, as may be seen in Fig. 20. The Borematic was chosen because of its suitability for demonstration. Most machines of this type have a single cycle of operation, and the pattern of machine functions is normally obtained by conventional methods. Quite often, the cycle necessitates a fairly

*"Magnetic Tape Control Applied to a Heald Borematic," *Machinery*, Vol. 84, page 1369.

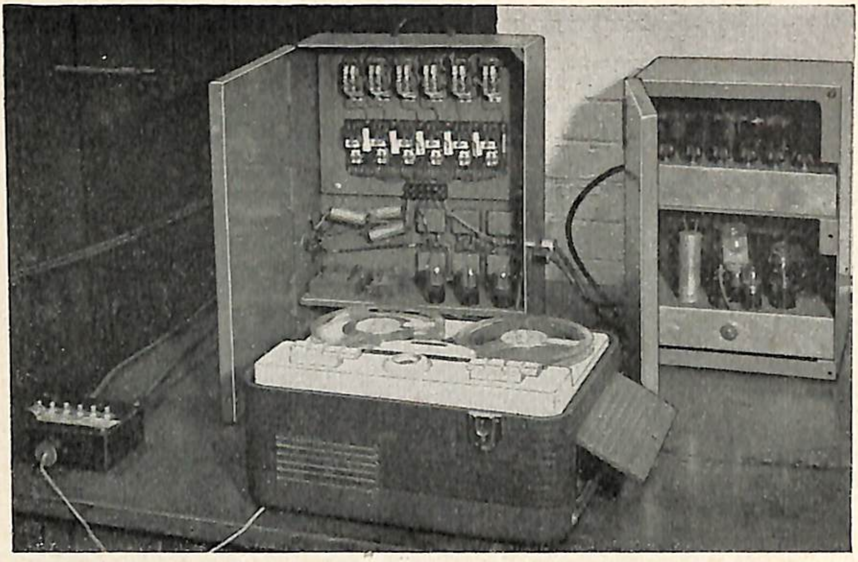

Fig. 20. The Magnetic-tape Control Equipment for the Heald Machine shown in Fig. 19

intricate circuit and a large number of limit switches and relays. Obviously, the more complicated the circuit, the more difficult it is to change or vary the cycle on a particular machine.

The magnetic-tape control equipment which has been developed reduces the work involved in changing a cycle to a minimum, and any cycle within the capabilities of the slides and elements provided on the Heald machine can be reproduced without altering the control circuit or the machine. The only limit to the length of cycle that can be recorded is the length of tape accommodated on a standard reel. One tape used has a playing time of one hour.

The conversion of the Heald machine was quite simple. All the limit switches and relays were removed, and only the main hydraulic motor and starter and the solenoid-operated valves were retained. The solenoid valves were connected directly to the slave relays, Fig. 21, which are actuated by reeds or tuned frequency circuits. Each of the reed relays or tuned frequency circuits is responsive to only one frequency, and each machine function has a separate controlling relay, The frequencies are generated separately by oscillators which work continuously. When a certain machine function is required, the appropriate push-button is depressed, to allow an electric feed of the correct frequency to complete the circuit to the reed relay which operates the slave relay controlling the solenoid valve. At the same time—and for the same length of time that the button is depressed—the frequency is impressed on the magnetic tape. At the end of the movement, the button is released and the recording is interrupted. This procedure is followed to record all the machine movements. If the

machining operation is such that a number of movements can take place simultaneously, the total combination of frequencies can be as easily recorded. When the cycle has been completed manually, the signals of each movement are inherently interlocked on the tape.

The machine and the recorder are returned and rewound respectively to their starting positions, and the recorder can be "played back" so

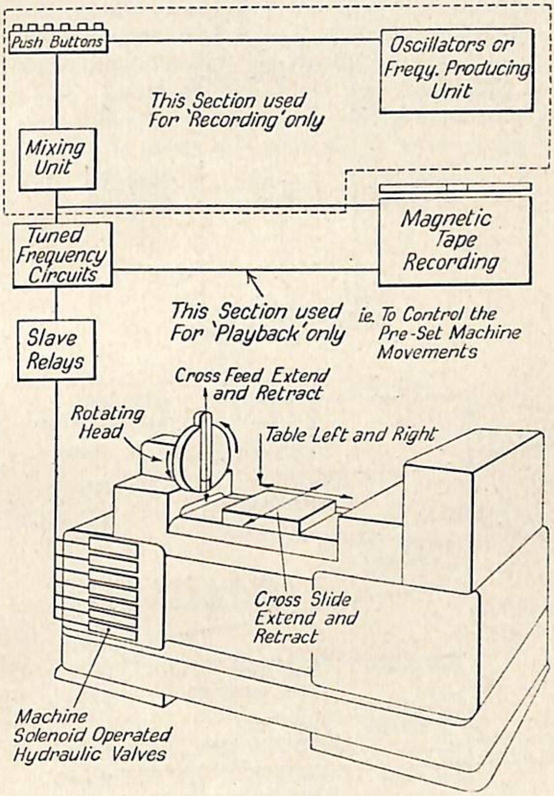

Fig. 21. The Herbert Magnetic-tape Control as applied to the Heald Borematic

that the frequency-responsive circuits, after sorting out the signals into their correct channels, will operate the solenoid valves in their original sequence and so reproduce exactly the operational cycle.

If, during recording, a mistake is made, the tape and the machine can be returned to the starting position, the signals on it erased, and a fresh recording taken. If a mistake occurs at the end of a long cycle, it is necessary only to erase the signal of the movement during which the mistake was made. In addition, the tape can be cut and spliced, and movements eliminated if not required.

The Heald machine was arranged to finish a special component to demonstrate the increased versatility with the new control. Three

different cycles of operation were employed to machine the components, and this would be normally impossible, or extremely difficult, to accomplish on one machine not equipped with a magnetic-tape control system. The cycles of operation and the component machined are shown in Fig. 22. The extreme accuracy required in machining is obtained on the Heald machine by the use of dead stops, and reliance is not placed

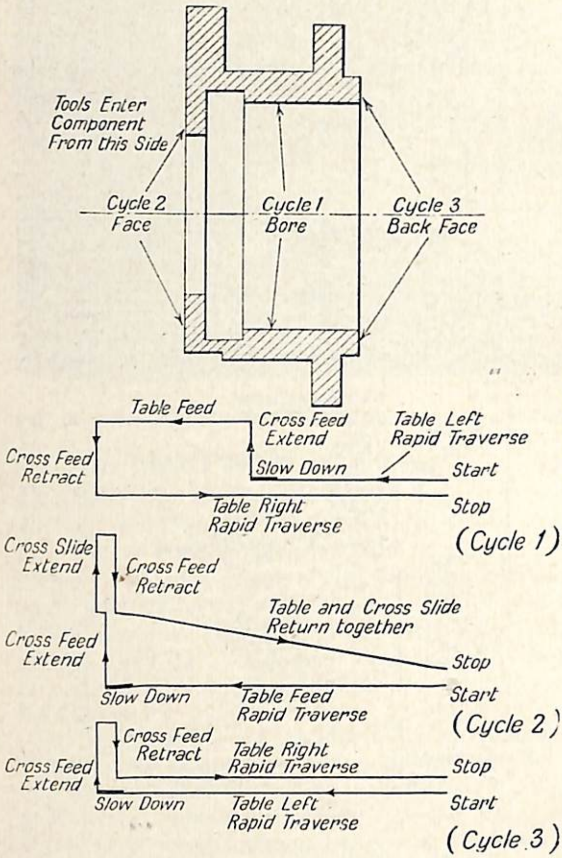

Fig. 22. For Machining the Component shown, Three different Cycles of the Heald Borematic are automatically controlled by Magnetic Tape

on the tape and its associated control for the final determination of machine movement. The system is thus used as a method of recording and reproducing patterns of machine behaviour and not of absolute measurement. The dimensional accuracy of the final machine movement is an inherent function of the machine. Before recording, the hydraulic circuit is preset to give certain rates of feed, and the recorded signal ensures that the slide squeezes against the dead stop when the hydraulic oil is at its lowest velocity. It is not considered economical to employ tape as an absolute reference of measurement for the set-up described, or, indeed, on any machine where dead stops can be used.

It is stated that any machine now operated by electro-responsive devices such as solenoids, magnetic clutches and servo-motors, could be operated by the Herbert system, and new work could be accommodated without complete revision of shop planning and layout, or alteration to the machines.

The company concerned do not suggest that it would always be desirable to convert all single-purpose machines, but many machines are often idle for long periods when a change in the design of a component or the introduction of a new component necessitates an alteration to the machine cycle. A further application would be to profiling and three-dimensional contouring. Large models could be eliminated and the forms preserved on tapes which are stored as easily as drawings. This type of application would be most effective if the tape could be programmed away from the machine.

CHAPTER 2

THE USE OF PERFORATED TAPE AND OTHER METHODS

A certain number of systems have been developed in which the required data is recorded in the form of punched or perforated tape, the perforations providing a direct means of control for the various functions of machine operation control, by the intermediary of electronic devices as in the case of magnetic tape control. Historically, the use of perforated cards or tape is the earliest form of automatic control, since this with mechanical means of implementation formed the basis of the automatic control of pattern in lace manufacture, and is the basis of some well-known type-setting machines used in modern printing. The punched-card method has also been extended and applied during recent years to business accounting and statistical machines. When the electronic computer was first devised, the punched-card machines offered a ready method whereby information could be fed into the computer, both for basic numerical information and for programming, i.e. prearranging the sequence of arithmetical processes that the computer was to follow in making use of the numerical data.

E.M.I. Developments System with Computer Control.* Some important investigations have been pursued by the E.M.I. Engineering Development, Ltd., in the field of automatic machine-tool control. The system that has been adopted makes use of analogue, as distinct from digital computing. This is claimed to afford a number of advantages for the purpose of machine-tool control. It was first employed, on an experimental basis, for controlling the table movement of a standard No. 2 Cincinnatti vertical milling machine with the workpiece mounted on a power-driven rotating table, which was coupled, through a servo-system to the table leadscrew drive. With this arrangement, flat cams and other plane forms, within certain limitations, could be produced, and the provision of a controlled vertical feed motion to the machine knee slide, taken through a flexible shaft from the rotating table drive, made it possible to mill three-dimensional cam forms. Some examples of flat cams produced on this machine are shown in Fig. 1, the triangular piece having sides $2\frac{1}{2}$ ins. long.

As a later development, the E.M.I. Company converted to computer control an electronically-controlled cam-milling machine built by

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*Based on a paper given by Mr. R. H. Booth at the I.P.E. Conference on "The Automatic Factory," *Machinery*, Vol. 87, page 144.

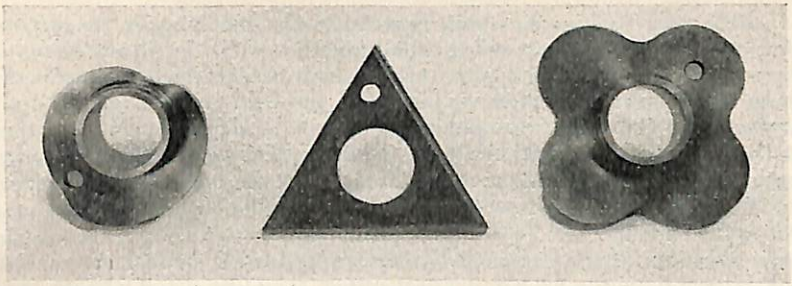

Fig. 1. Examples of Flat Cams milled on a Punched-tape controlled Machine

Research Engineers, Ltd., whereby flat cams and other workpieces can be milled to form without the use of a master. This machine, as arranged for computer control, is shown in Fig. 2.

The principal alteration to the machine has been the bridging of the rotating table whereon, previously, the master cam was mounted, with the computer control unit seen immediately to the right of the work table. Projecting from the right-hand end of this unit is a horizontally-moving leadscrew which makes contact with the stylus, and, under computer control, simulates a master cam and enables the required form to be produced on the workpiece.

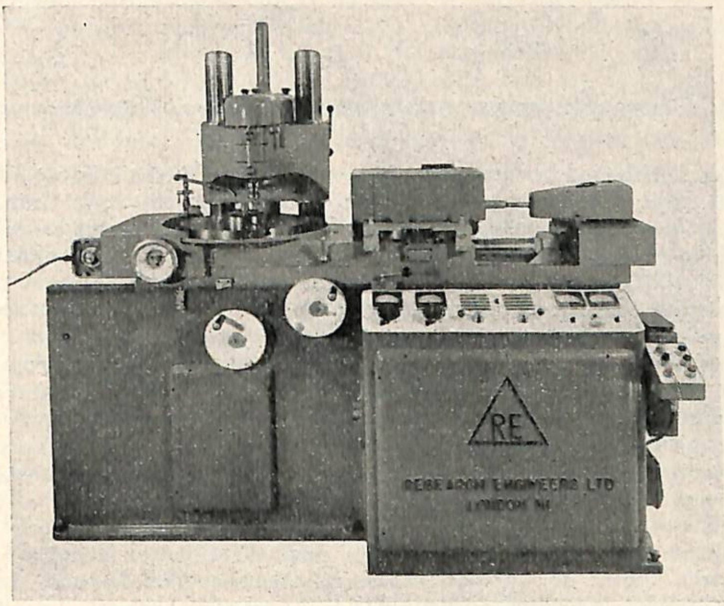

Fig. 2. The Electronically-controlled Cam-milling Machine built by Research Engineers Ltd., and converted to Computer Control by E.M.I. Engineering Development, Ltd.

Referring to Fig. 3, which represents the machine in its original form, the 18-in. diameter work table, together with the 18-in. diameter copy table, is carried on a main table which is traversed longitudinally along an intermediate slide by means of the leadscrew *A*, driven by a servo-motor *B*. The intermediate slide can be adjusted and clamped on the main bed for positioning the work in relation to the cutter during setting up, or for applying a cut, without disturbing the copying control.

Carried on the intermediate bridge is a bridge on which is mounted the stylus head. The follower *C*, which is fitted with a roller of the same diameter as the cutter, is lightly spring-loaded against the master, and at the centre is hinged a small mirror whereby a light beam from

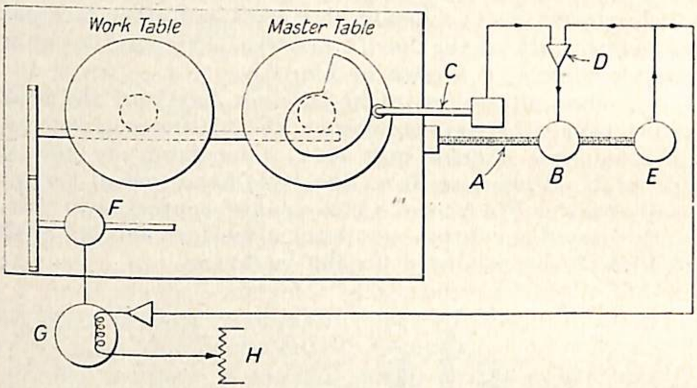

Fig. 3. Diagrammatic Arrangement of the Cam-milling Machine as Originally constructed

a lamp is reflected towards two photo-cells carried in the housing on the stylus head. When the system is in equilibrium, the light from the mirror shines equally on both photo-cells, so that the currents generated by them are equal. These currents are fed, by way of an amplifier *D*, to the splitfield servo-motor *B*, which is connected to the main table traversing screw by gearing, and, when the currents are equal, the motor does not run. As the tables turn, and with them the workpiece and master, the latter causes the stylus to move towards or away from the table centre, tilting the mirror one way or the other of the motor windings. As a result, the motor runs in the required direction to move the table sufficiently to return the mirror to its central position. A follower movement as small as 0·0001-inch is sufficient to cause the servo-motor to operate, to correct the main table position.

In the original arrangement now being described, the work and copy tables are driven synchronously through reduction gearing by a $\frac{1}{4}$-h.p. d.c. motor *F*, supplied with current from a Ward-Leonard set *G*, which enables the speed of the table to be varied steplessly from one revolution in six minutes to one revolution in sixty minutes, the speed being selected on the rheostat *H*.

When cams with unusually steep rises are to be cut, the rapid movement of the follower in negotiating the profiles would normally cause the servo-motor to run at excessive speed, in order to move the main table sufficiently fast. Such rapid movement would be undesirable for two reasons. On the one hand it would tend to introduce errors in the copying action, and, on the other, might result in excessive feed of the work against the cutter. To avoid these defects, an a.c. generator E is coupled to the servo-motor, and its output is amplified and fed into the Ward-Leonard set which controls the turntables, in such a manner as to slow down their speeds of rotation. At slow servo-motor speeds, the output is very small and has very little influence, but as the speed of the servo-motor rises, the table speed is reduced in accordance with requirements.

Application of Computer Control. In carrying the automatic control a stage further, to the extent that the machine is operated on the basis of information taken direct from the drawing, so that the need for a master is eliminated, computation is necessary at the machine, since the position of the table depends upon more than one item of information.

The data given on a drawing concerning a cam curve are rarely continuous, and are usually presented in the form of a table of co-ordinate or angular and radial dimensions, and, as such, must be fed by some means into the machine tool which is to produce the workpiece.

The medium adopted for the E.M.I. control system is the punched-tape technique, and the meaning of the various hole positions in the punched tape may be illustrated by an example. Let it be assumed that it is required to record the dimension 3·546, which may be a radius in inches, and one of many given in succession, representing cam radii at equally-spaced angles.

An important consideration is that the punching of holes shall be a straightforward task, requiring a minimum of mental effort, and this calls for the provision of separate, correspondingly numbered keys, which are depressed on the tape punching machine for each of the numbers, to produce the prescribed hole pattern. This requirement leads to the use of the binary decimal code, which provides four possible hole positions. In the combination actually used in the E.M.I. system the required dimensions are made up of the powers of two, 2^0, 2^1, 2^2 and 2^3, that is 1, 2, 4, and 8, as shown in Fig. 4 at X. This constitutes a code system which is used for every decimal digit in turn. The groups of holes may be placed side-by-side on wide tape as at the top of Fig. 4, or vertically, one after the other, on a narrow tape, as shown at the left. Although the details of the mechanism for reading the two tapes will differ somewhat, the overall function and result is the same. If a standard teleprinter be employed, four out of the five available hole positions across the width of the tape can be used for the numbers of the dimensions, the fifth channel being available for initiating command signals for the various machine controls.

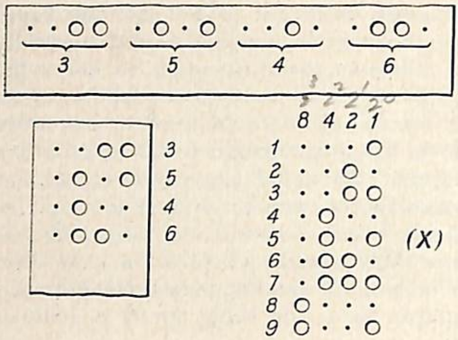

Fig. 4. Binary-scale Code System used for Punching the Tape

It is important to appreciate that there is no difficulty in achieving any desired accuracy in the recording of information in this way. With the narrow-tape method, it will be seen that there is no great problem in adding decimal digits to an ordinary row of figures, and, since the function of the holes is only to allow fingers to operate electrical switches, the tape reader and machine tool are called upon only to distinguish between one row of holes and the next.

However, the hole pattern cannot be used by itself to control the table position, since then the table would do no more than proceed in a series of steps from one dimension to the next. Thus some semblance of the required shape could only be produced if the points on the tape referred to very small increments of angular movement. If, however, two points at a time are used by the machine, an indication of the next movement required being communicated, the difference can be effected by a constant rate of traverse of the main longitudinal table. The diagram of Fig. 5 shows how the cam milling machine could be

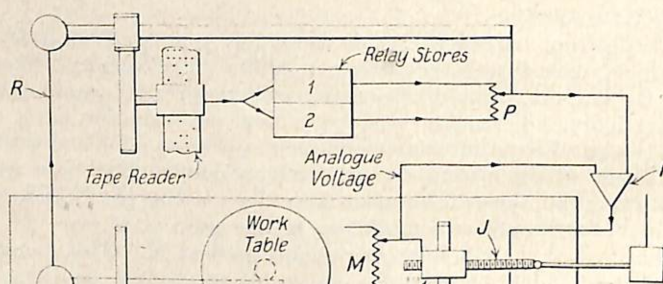

Fig. 5. Diagrammatic Arrangement which indicates a Possible Conversion of the Cam-milling Machine to Automatic Control by means of Punched Tape and adopting Linear Interpolation between Plotted Points

modified to operate under punched-tape control and incorporating the system of linear interpolation just outlined. The rotary table carrying the master cam has been replaced by a leadscrew *J*, working in a nut *K*, and bearing on the copying follower. Operation of the leadscrew and nut by the motor *L* actuates a potentiometer *M*, whereby a varying feed-back voltage is derived, which is fed into an amplifier *N*, together with a voltage from the potentiometer *P*, associated with the punched tape control. The motor *L* drives the leadscrew until the voltage from the potentiometer *M* balances the control voltage from the potentiometer *P*, which is derived from the punched tape.

The arrangements for driving the work table are unaltered, but a synchronous electrical link by Magslips as indicated at *R* has been added between the table and the tape reader. The latter thus proceeds from line to line on the tape as the table rotates, a process equivalent to running down a table of dimensions, and as the new line comes it is retained or "remembered" until the next line is available, thereby forming the means whereby two points on the contour being machined are used together.

This "memory" function is obtained by means of relays, which are energised as the tape passes through the reader. On each relay, contacts are closed to switch in a voltage proportional to the significance of its associated hole in the tape. The two voltages in question are applied to opposite ends of the potentiometer *P*, the slide of which is driven, together with the tape reader, through the synchronous link *R*. A duplicate of the potentiometer *P* may be incorporated in the system, to facilitate changeover from one pair of reference points to the next pair.

The overall effect of the circuit is to traverse the leadscrew in such a way as to trace a figure represented by the figures given in the original data and recorded on the perforated tape. The table, therefore, takes up a longitudinal position relative to the cutting tool corresponding to the polygonal figure dictated by the punched tape.

Although there will not now be any sudden jump in the position of the stylus leadscrew *J*, its rate of movement will change suddenly as each point comes in, so that the resultant shape has sharp corners. This defect can be remedied if the control system is arranged to take notice not only of the next point but also the one after that. By this means, the curvature of successive lines, each now passing through three points, can vary in such a way as to make each line touch or blend with its neighbours.

It is this system of parabolic interpolation which has been adopted for the modified cam-milling machine shown in Fig. 2. To make use of three points instead of two requires additional relay "stores", also a parabolic bridge, a unit which replaces the potentiometer *P* of Fig. 5. The arrangement of the modified system is shown in Fig. 6.

The parabolic bridge is shown at *X* in Fig. 7, and an example of a curve representing a plot of radius against radius (i.e. in polar co-ordinates) is given at *Y*. The points *A*, *B*, and *C*, on this curve are equally spaced in angle. Voltages are available from the relay

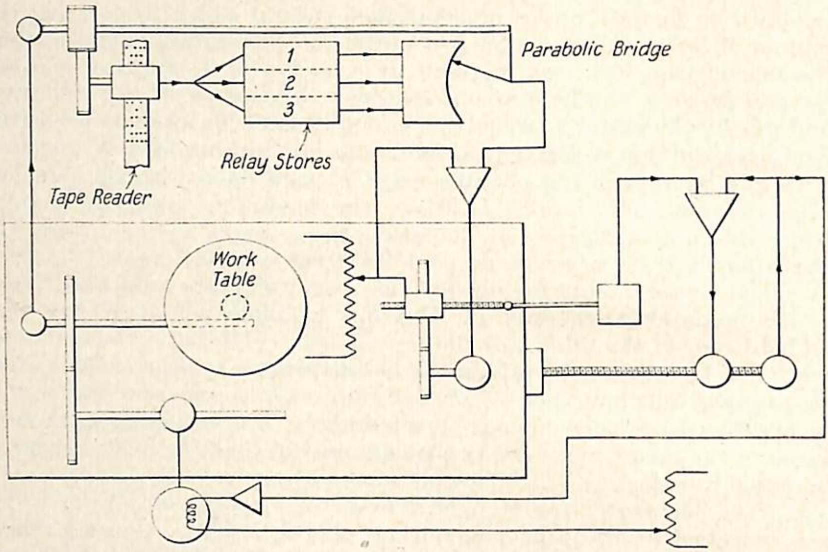

Fig. 6. Diagrammatic Arrangement of the Cam-milling Machine converted for Control by Parabolic Interpolation

stores which are proportional to the three radii, and it is required to produce intermediate voltages lying on a parabola drawn through *ACB*, a parabola being the simplest curve which will produce the blending as already described. The line *AB* may first be drawn, and is equivalent to the potentiometer *P*, in Fig. 5. The mid point of the line is indicated at *M*, and *N* is any point on the line *AMB*. Referring to the circuit of the parabolic bridge at *X*, the auto-transformer *AB* is supplied with the voltages corresponding to the points *A* and *B*

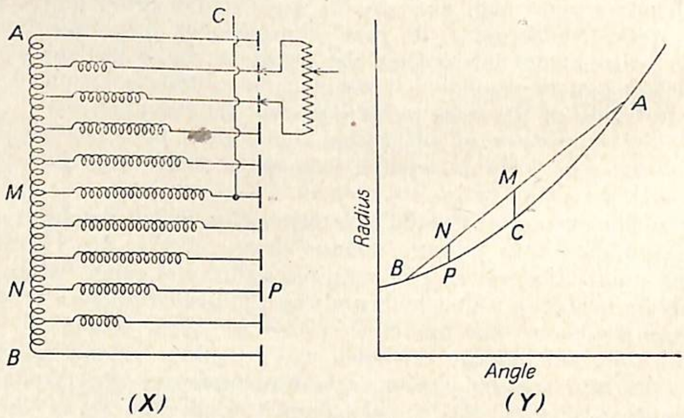

Fig. 7. Arrangement of Parabolic Bridge

on the curve, and a series of tappings on it give voltages corresponding to M and N. The primary of another transformer is connected between M and C, and carries the voltages corresponding to the points M and C on the curve. Secondary windings are provided on this transformer, the turns of which vary according to the parabolic law. For example, if MC have 5^2 turns, the successive secondaries have $5^2–2^2$, $5^2–3^2$, and $5^2–5^2$ ($=0$) turns. One end of each of these secondaries is connected to the appropriate tapping of the transformer winding AB, and the opposite ends then carry voltages as referred to the curve ACB, the point P, for example, being derived from the tapping N. The gaps between the voltages produced by the secondary windings can be filled in lineally by a potentiometer across the slider of the bridge. The latter is rotated uniformly through the medium of a synchronous link

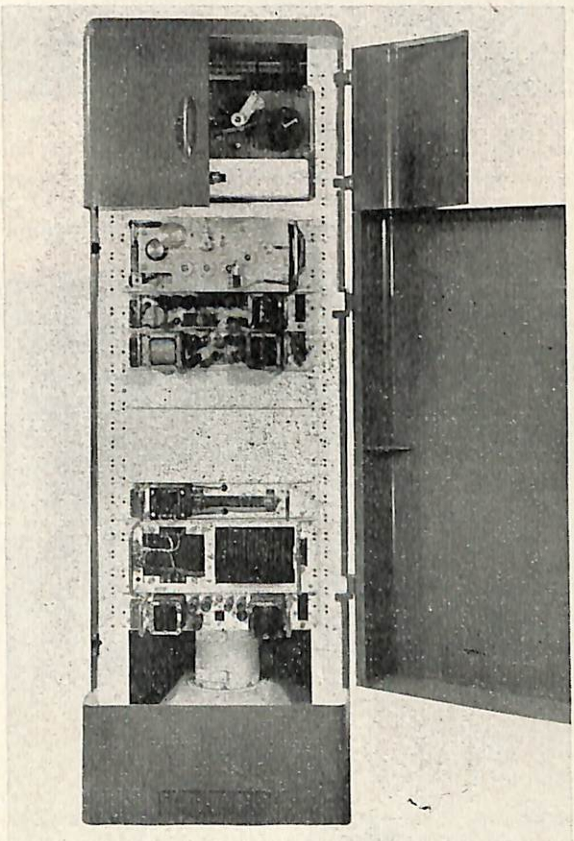

Fig. 8. The Control Unit containing the Tape Reader and Associated Equipment which is coupled to the Cam-milling Machine and provides for Automatic Control by Parabolic Interpolation

from the work-table drive, which also effects indexing of the tape. In practice, two bridges are used, so that a smooth changeover is obtained from one set of contacts to the rest.

The electrical circuit is so arranged that, initially, three dimensions must be read from the tape before the system becomes operative, and upon movement of the tape to bring the fourth row of holes into position, the signal originated by the first is cancelled. This overlapping sequence then takes place continuously as the tape is read.

TAPE READER AND CONTROL EQUIPMENT. The control unit containing the tape reader and associated equipment which has been constructed for the cam-milling machine is shown in Fig. 8. The tape reader is shown at the top, and, immediately beneath, is the parabolic bridge interpolator. Below the latter is housed the power pack. The banks of relays which serve as "stores" are contained in a compartment at the rear of the cabinet. A close-up view of the tape reader is given in Fig. 9. The speed of indexing of the tape depends on the speed of rotation of the work table, because of the synchronous link. The leadscrew unit, which replaces the rotating master table on the machine, is seen with the covers removed in Fig. 10. Since the accuracy of reproduction depends directly on the precision of the leadscrew, the latter must be made with special care.

The tape used in this installation is in the form of 70-mm. wide film which is punched as required by means of a keyboard. In this

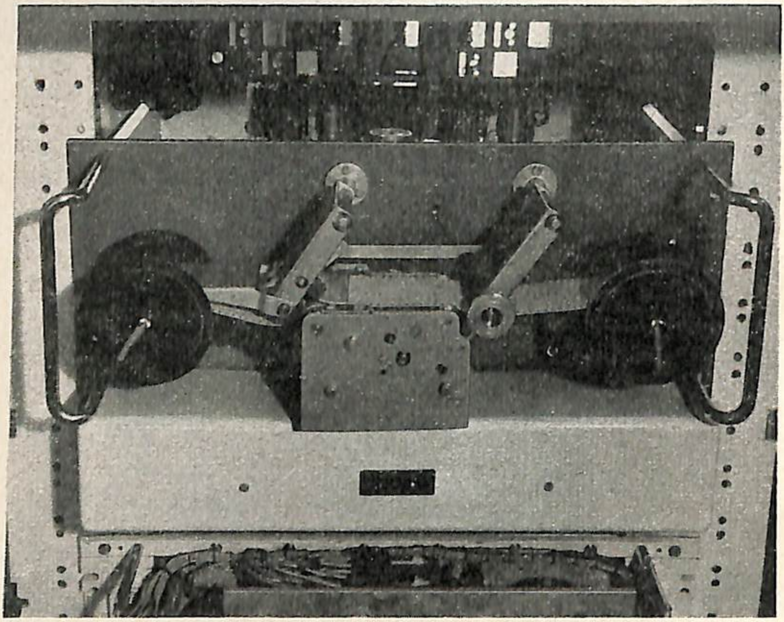

Fig. 9. Close-up View of the Tape Reader in the Control Unit

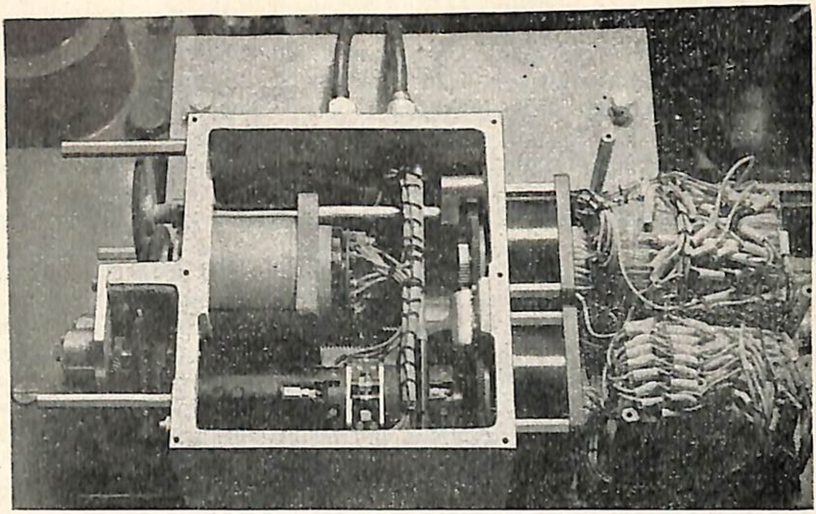

Fig. 10. The Leadscrew Unit with Covers removed

instance a proprietary make of adding machine has been adapted for the purpose, the adding mechanism being removed. This is shown in Fig. 11. The printing mechanism was, however, retained, so that,

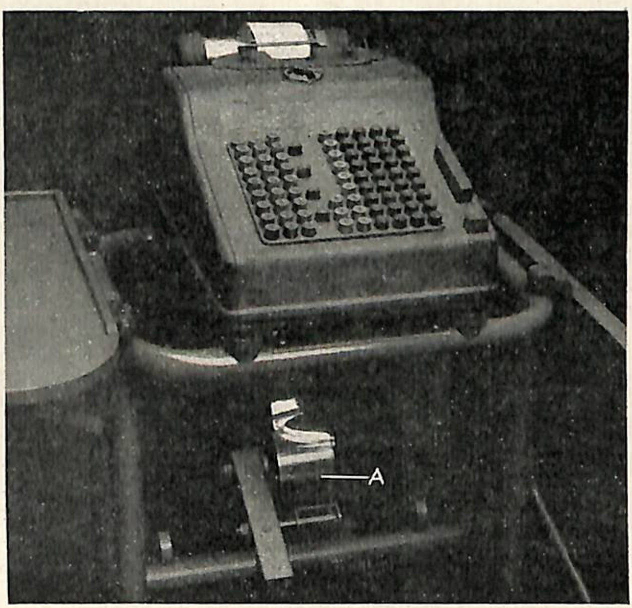

Fig. 11. The Calculating Machine Keyboard which has been adapted for punching the the Tape used for Machine Control

when the number keys are depressed, the figures are printed on a continuous paper tape at the same time as the holes are punched in the film. The reel of paper is seen above the keyboard in Fig. 11, and this enables a check to be made to ensure that the film has been correctly punched. A gear drive has been taken from the existing drive arrangement, for indexing and winding the film on and off the spools, also for actuating the punching mechanism. The film is seen being taken for punching from the spool indicated at *A*, below the machine.

ANALOGUE COMPUTING. It will be apparent that with the system described, the automatic control function is obtained by reference to the actual values of voltages as indicated by holes punched in the tape, the holes being selected to represent dimensions and angles. This form of control is based on analogue computing, since a length or angle is represented as a voltage. For any physical quantity there exists a limit to the accuracy with which it can be known, but this factor is not important in computing, provided that the analogue quantity, in the present case a voltage, can be known more accurately than the value that it is representing.

With the exception of jig-borers, it is considered doubtful whether machine tools in general are more accurate than one part in 10,000, i.e. 0·001-inch in 10 ins., and this is the degree of precision which has been taken as a basis in designing the computing circuits for the equipment now described. It has also been stated that it is possible to effect voltage ratios to an accuracy of one part in 50,000 at least, so that no difficulties should be encountered in designing suitable electrical circuits.

An advantage of the type of analogue computing adopted is that the voltages which represent dimensional variations can be readily combined and modified by potentiometers, also by means of transformers, if a.c. voltages be used. Another advantage is that the electrical equipment required can be robustly constructed, yet accommodated in a small space, which is of considerable value in machine-tool applications.

An example* of a more general type of application of the E.M.I. system is afforded by its use on a Cincinnati No. 3 vertical milling machine, for controlling the longitudinal and transverse movements of the table, thereby enabling internal and external two-dimensional forms to be produced automatically. This machine, which is illustrated in Fig. 12, together with the tape-control equipment, is to be used by the Bristol Aero-Engine Co., Ltd.

In this instance, the conversion was very simply effected, since the degree of precision required was such that the existing table and cross-slide lead-screws could be retained. All that was necessary was to couple the two servo-motor units directly to the lead-screws in place of the normal traversing handwheels. The feed-back voltages whereby the table position is signalled continuously to the control unit are

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obtained from the rotation of the lead-screws, through gear trains which actuate the slides of compound potentiometers. Where greater accuracy is required, systems employing optical gratings, or master lead-screws operating under no-load conditions can, of course, be applied.

The servo-motors, of $\frac{1}{4}$-h.p., drive the lead-screws through 100-to-1 ratio worm gearing, which at the maximum servo-motor speed of 6,000 r.p.m., provides a feed rate of 15 ins. per minute. The overall feed rate can be steplessly varied by adjusting a rheostat on the control panel mounted on the left of the machine head, and push-button

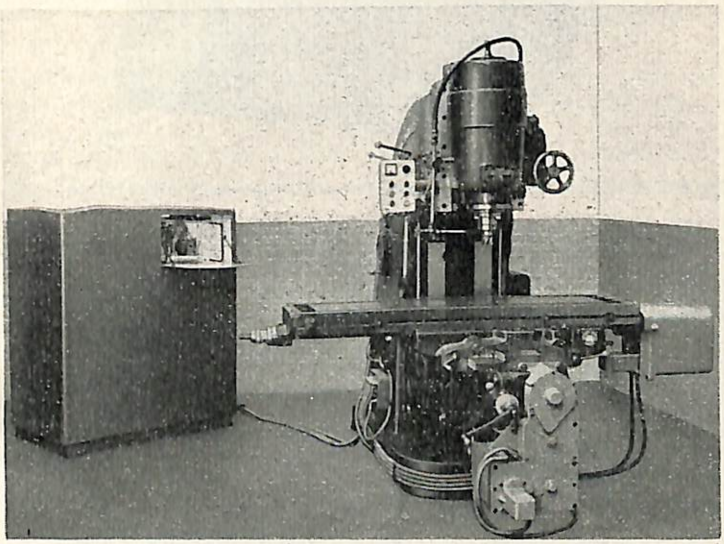

Fig. 12. A Cincinnati No. 3 Vertical Milling Machine fitted with E.M.I. Tape Control for the Longitudinal and Transverse Motions of the Table

operation for the servo-motors can be provided. The normal feed drive of the machine is disengaged, but could be uncoupled, if required, to obviate the load resulting from unnecessary rotation of gear trains and shafts.

The control equipment shown is basically capable of reproducing a form to an accuracy of 0·001-inch. The precision obtained, however, depends on the accuracy of movement of the machine slides and the amount of back-lash in the lead-screws. A useful feature of the system is that, after ascertaining the amount of back-lash present, it can be allowed for when the tape is being prepared. The servo-motors then rotate an additional amount to take up the back-lash at the relevant points in the machine cycle. This procedure was employed when the machine was being used for the production of light-alloy wave-guide members required to a high degree of accuracy, which it would have been impracticable to produce from the solid by normal machining processes.

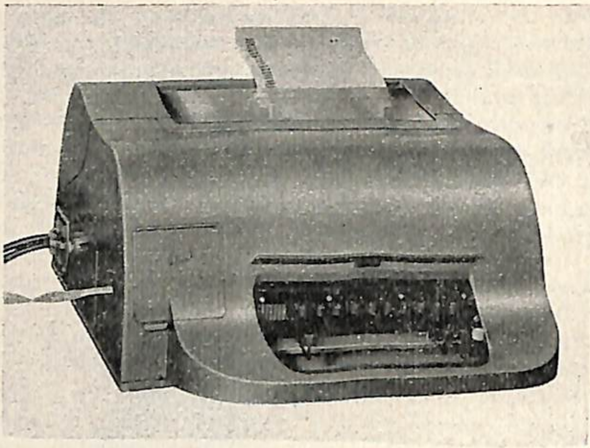

Fig. 13. The Creed Teleprinter used for producing the Punched Paper Tape

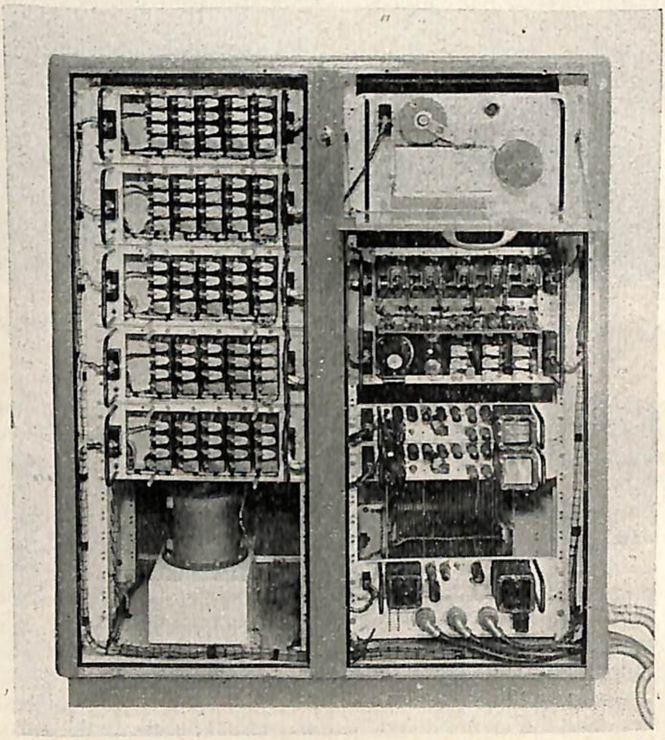

Fig. 14. View of the Control Equipment containing the Relays which store Information, the Interpolater, the Servo-control Units, and the Tape Reader

An important alteration to the system since it was applied to the cam-milling machine is the use of a standard Creed teleprinter, as seen in Fig. 13, and the normal paper tape, which has been found to serve the purpose equally as well as the celluloid tape previously employed. Certain keys, not required, have been removed from the teleprinter. A standard Creed tape-reader mechanism is incorporated in the machine-control unit. A view of the latter, with the front cover removed, is given in Fig. 14. Relatively few valves are used in this control unit, and all the relays are of standard types.

At the time of writing, it is understood that it is proposed to extend the application of the E.M.I. system to a variety of other types of machine and operations.

Tape-controlled Precision Boring Machine.* The punched-tape principle of operation has been applied to a precision machine used for boring shaft holes in instrument gear-train plates. A system developed by the Minneapolis-Honeywell Regulator Co., U.S.A., is employed in conjunction with a standard 4-spindle Ex-Cell-O precision

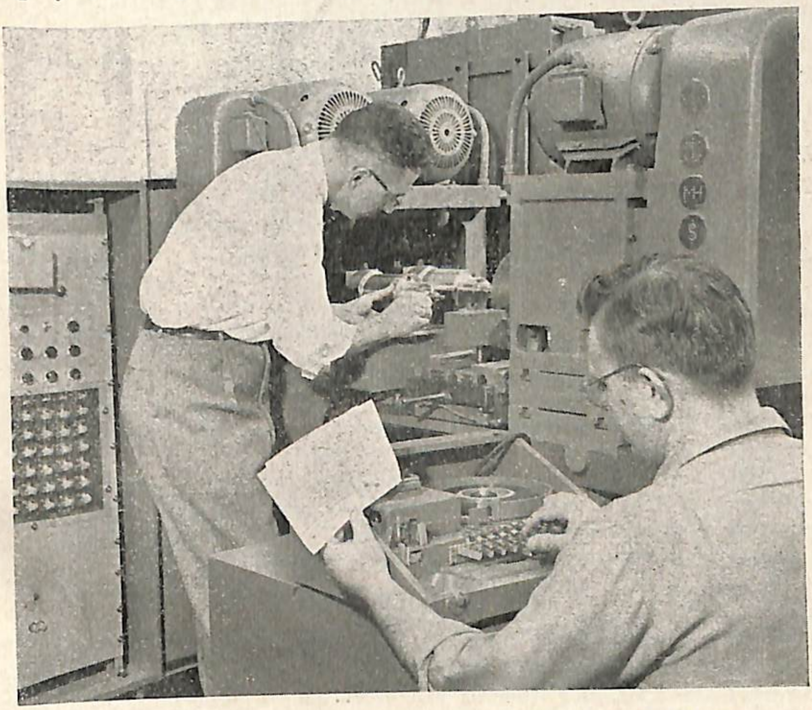

Fig. 15. Using a Machine similar to a Typewriter, the Operator in the Foreground punches Hole Co-ordinates and Feed Instructions in the Tape which is used to control automatically the Operation of the Modified Boring Machine seen in the Background

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boring machine which has been modified with built-in electronic controls.

Hole co-ordinates and feed instructions are punched on the tape by a perforating machine similar to a typewriter. Electronic signals from the tape regulate the linear travel of the hydraulic cross-slide of the machine, and also the rotary motion of the special holding fixture mounted on the cross-slide. Tape preparation is said to occupy some five minutes per hole, and the complete changeover from one part to another can be accomplished in approximately 30 minutes.

For automatic operation, the punched tape is placed in the reader of the control circuit. After placing a workpiece in the fixture, the operator merely presses a button to initiate the automatic tape-controlled cycle. After the machine has performed the whole cycle of operation, during which it has read the complete strip of tape, it stops to permit the removal of the finished part.

When only a small number of parts is needed, the machine can be operated manually. With either manual- or tape-controlled operation, co-ordinate information is fed to the machine in increments of 0·0001-inch over the available 8 inches of linear range, and in increments of 0·01 deg. over the 360-deg. rotary range. Accuracy is claimed to be within plus or minus 0·0005-inch. Operation of the tape recorder is shown in Fig. 15.

Monarch Programme Control.* A numerical sequence programme control unit for use on Monarch lathes has been introduced by The Monarch Machine Tool Co., Sidney, Ohio, U.S.A., to enable the selection of fully-automatic work-cycles. In Fig. 16 the unit is shown being used in conjunction with the Company's 10-inch, series EE, centre lathe.

Control is obtained electronically, the panel on the right incorporating a series of simple push-button selectors for presetting the required cycle of motions, and for selecting up to five different speeds and feeds for use during the cycle. Operating in conjunction with the control panel is an analogue-to-digital converter coupled to the lathe carriage. Electrical impulses from the converter are fed to the control circuit at the required instants during the automatic cycle, thereby initiating the various operations called for by the settings of the selectors on the panel.

The selector settings can be changed manually, or a master board can be used which is designed to depress simultaneously all the push-buttons required for a particular cycle. Another method is to use punched cards prepared by the methods department. These are placed over the panel to indicate which buttons are to be depressed for a given cycle, or sequence of operations.

The control cabinet is mounted on casters so that it can easily be moved to the most convenient position for operation. All the electronic components contained therein are mounted on plug-in chassis which can be quickly and easily removed for servicing. All the units are electrically interlocked, so that the removal of a chassis from the cabinet causes the machine to be switched off.

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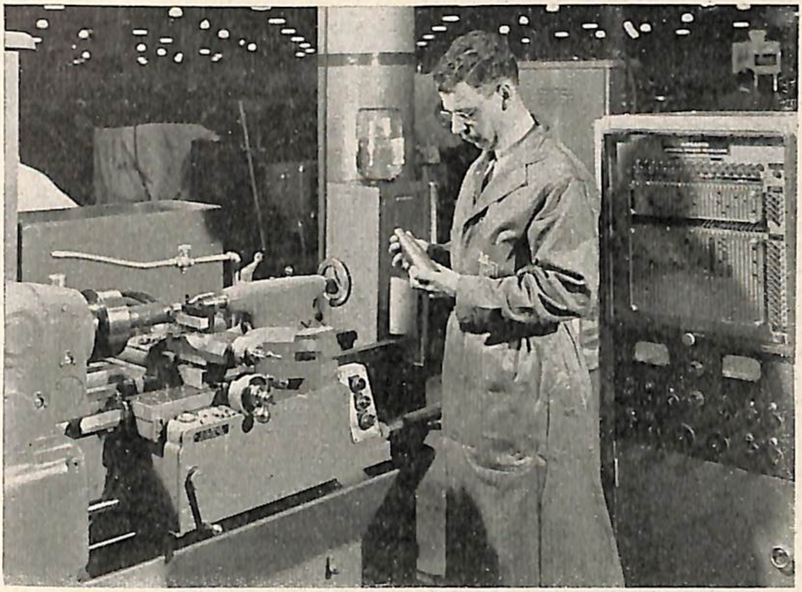

Fig. 16. Monarch Programme Control Unit based on a Numerical Sequence System being employed on a Monarch Centre Lathe

The programme unit can be used in conjunction with the company's Air Gage tracer incorporating a dual-template system whereby the last roughing and finishing cuts may be taken automatically under template control.

"Industrial Controls" System.* An automatic system which provides a relatively simple, accurate and reliable electronic control for the automatic operation of machine tools, including milling, grinding and boring machines, lathes and presses has been incorporated in a convenient unit by the Industrial Controls Corporation, Chattanooga, Tenn., U.S.A. This operates from information presented by punched, printed or magnetized tape, or from other suitable record of the essential data. Such information may be automatically picked-up by the unit by means of photo-cells, magnetic pick-ups, contacts or capacitors. In the system as at present applied the sensing means adopted is the photo-cell.

This control system is based on a special step motor, which rotates in small steps or increments and is magnetically locked in position when stopped, so that there is no over-travel. Free-wheeling is thus prevented, and it is possible to employ the motor as a combined indexing and power device for producing definite specified displacements.

By means of suitable gearing, each step movement of the motor can be caused to move a cutting tool, or any other member of an

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automatic system, through a small distance such as 0·0001-inch or less. The number of steps may be chosen to meet particular requirements. For example, with an automatic control of this form which has been applied to a milling machine, there are 108 steps per rotor revolution, and the gearing has been designed so that one step movement of the rotor displaces the cutting tool by a distance which is slightly less than 0·001-inch. A relatively smooth shape of any desired shape is thus obtained.

Another feature of the step motor is that it can be reversed in a fraction of a second, when operating at moderate speeds. Also, when it is used with the associated servo-system or control system and a special mechanism there is no hunting.

In Fig. 17 is shown a three-dimensional milling machine for which a corresponding three-dimensional control has been built, incorporating three of the step motors. One motor controls the vertical movement

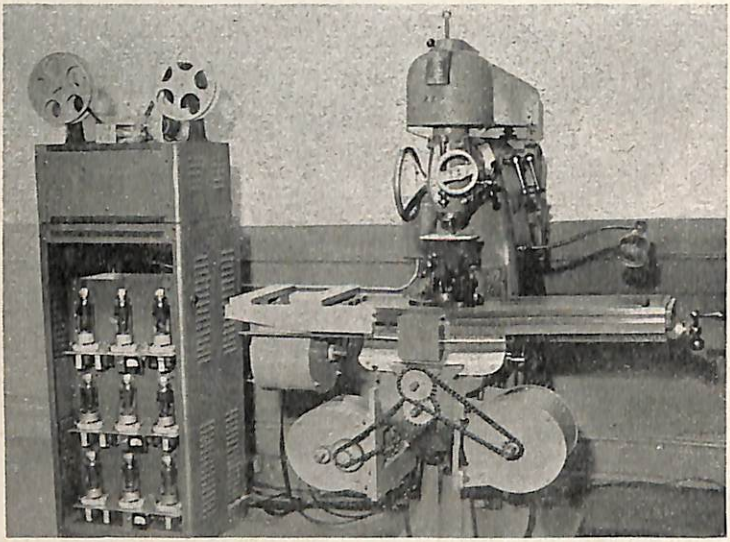


Fig. 17. Milling Machine equipped with an Automatic Control System in which Three Step-Motors are employed to move the Tool and Workpiece

of the cutting tool relative to the workpiece, and two others control the movement of the table along axes that are mutually at right angles in a horizontal plane. Nine thyratrons control the current to the motors, and six photo-cells sense the punched, printed or photographed tape, which in the given example consists of a 35-mm. cinema film.

A small motor traverses the film across six small windows which admit light from a lamp to the corresponding photo-cells when a punched hole or clear portion of the tape or film is in register with a

window. The tape therefore serves to control the light reaching the photo-cells in accordance with the printed or punched pattern. Change of speed of the tape does not alter the shape of the workpiece cut by the machine, but merely varies the cutting rate.

Each mark or hole on the tape causes a one-step movement of the associated motor on the milling machine, so that the latter produces a shape corresponding to the tape pattern. The longitudinal spacing of the marks determines the speed of the step-motor. A fourth step-motor can be used to rotate or shift the workpiece, and additional step-motors may be used for other purposes.

The milling-machine control incorporates an automatic back-lash compensator, which requires to be set only the once.

In connection with this automatic control system, a machine has been developed whereby a drawing or template is traced manually or automatically and a tape is simultaneously printed or punched.

CHAPTER 3

POSITIONING AND MEASUREMENT SYSTEMS

Developing side-by-side with the methods of machine control have been a number of systems whereby a given dimension may be readily obtained by an automatically operated displacement, also, certain systems which are able to relate a dimension accurately to other useful functions which in turn may be usefully applied to automatic measurement or control. Certain methods have already been seen applied in some of the examples of the previous chapters, but in the present chapter the systems treated have somewhat special applications or present somewhat novel features.

B.T.H. Automatic Positioning System.* An electro-magnetic system for accurately positioning machine-tool tables and slides has been developed by the British Thomson-Houston Co., Ltd. The essential elements of this system comprise a length bar, usually attached to the machine bed or column, and a detector head mounted on the under side of the table or other sliding member which is to be positioned.

Referring to Fig. 1, the length bar is composed of a steel member *A*, of channel cross-section, wherein are bored the holes *B* at 1-inch spacing, and of diameter which provides a clearance for integral,

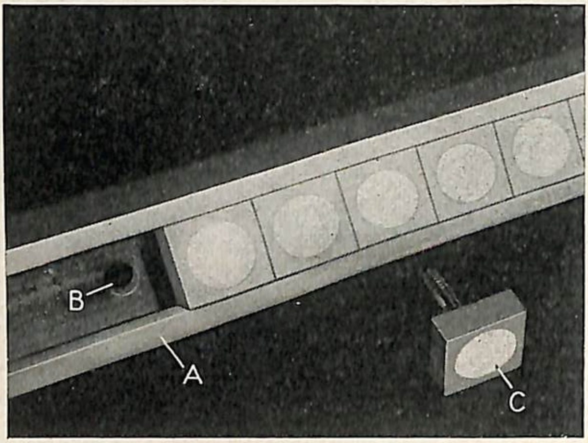


Fig. 1. Part of the Length-bar Assembly used in the B.T.H. Electro-magnetic Positioning System for Machine-tool Tables and Slides

*"B.T.H. Automatic Positioning System for Machine Tables and Slides," *Machinery*, Vol. 87, page 262.

threaded shanks on a series of steel blocks *C*. At the centre of each of these blocks is fitted a $\frac{3}{4}$-inch diameter plug of brass or other non-magnetic material. The blocks are a tight fit across the width of the channel, but are slightly less than 1-inch long, so that they may be readily adjusted and clamped to produce a pitch dimension of precisely 1 inch for the brass inserts along the length of the bar.

The length-bar assembly is fastened to facings on the machine bed, and located endwise to prevent movement. The bar has about the same coefficient of thermal expansion as cast iron, so that it expands

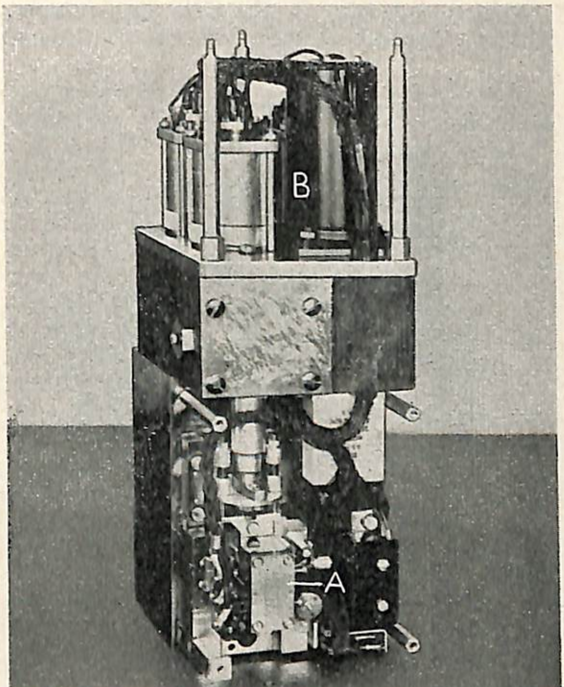


Fig. 2. The Detector Head used in conjunction with the Length Bar

and contracts equally with the machine bed. Thus if the workpiece be of ferrous material, variations of shop temperature are largely compensated.

The electrical detector head, seen removed from the machine in Fig. 2, incorporates a differential transformer in a housing at *A*, which is arranged to move in the direction of the table traverse motion, forwards or backwards, along precision guideways in the head. This movement is effected by an accurate leadscrew which is driven through gearing by a servo-motor *B*. The face of the transformer housing is covered

by a brass plate, which is bored to accommodate the ends of two round pole-pieces, at $\frac{3}{4}$-inch spacing, of the differential transformer.

These pole-pieces are flush with the surface of the brass plate, and when the detector head is assembled in the machine, the plate is located a few thousandths of an inch from the faces of the inserts in the length bar.

The control desk associated with the B.T.H. automatic positioning system is shown in Fig. 3. It incorporates two rows of six dials which enable co-ordinate dimensions of two integers and four decimal places to be selected manually. Considering one row of dials, the first two referring to the tens and units of the dimension selected control the setting of a master synchro (Magslip) in the control cabinet, which

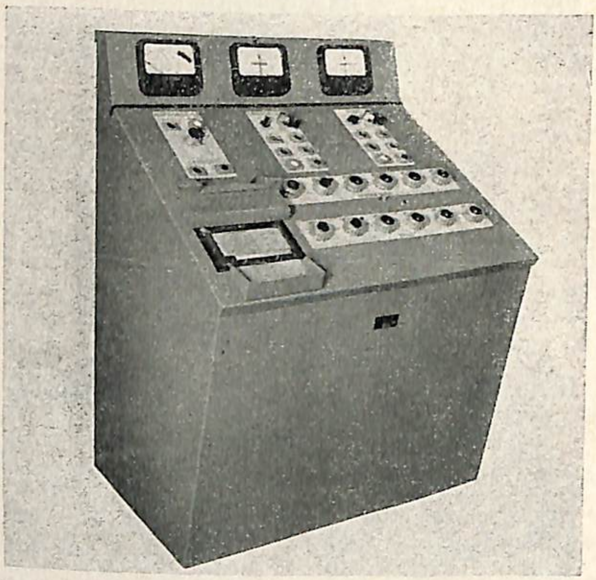


Fig. 3. The Control Desk for the B.T.H. System, on which the Co-ordinating Dimensions are selected by Dials

is coupled electrically to a corresponding synchro in the main feed-box of the machine. The four dials concerned with the decimal portion of the dimension provide for the setting of three master synchros in the cabinet, which are associated with three synchros in the detector head.

As soon as the dials are set, the servo-motor *B*, Fig. 2, rotates until, under the control of the three associated synchros, the differential transformer is traversed along its slideway by the leadscrew through a distance corresponding to the decimal part of the dimension. No action is required on the part of the operator. Depression of a push-button starts the driving motor in the main feed-box, and rotation continues until, under the control of the associated synchros, the table has been moved to within 0·25-inch of the required position. Control

of the feed motor is then switched to the detector head, and the table slowly brought to its final position, as determined by the differential transformer in conjunction with the length-bar assembly. If a distance greater than 0·5-inch has to be traversed, rapid traverse is automatically engaged for the slide movement.

The differential transformer is fed with constant current at a frequency of 50 cycles per second, and, when the two pole-pieces are out of symmetry with a brass insert in the length bar, there is a greater voltage across one winding than the other because of the difference in the reluctance of the two magnetic paths. The phase and amplitude of the output voltage depends upon the direction and the amount of pole displacement. This output is fed into the main servo-system, and causes the feed motor to run until the table is in the required position, that is to say, until the reluctance of the magnetic paths are equal, and the output voltage from the differential transformer is zero.

Provision is made in the electrical circuit whereby the motion of the table is reversed in the case of over-run, so that the approach to final position is always from the one direction, thus ensuring that any errors due to clamping, mechanical creep, or skewing of the machine slides are always in the same direction, and hence negligible.

When the table comes to rest in its final position, it is automatically clamped, and thereafter the selector dials can be set immediately to the next dimension required. A "coincidence" meter is provided to show the operator that the final position has been accurately obtained. Provision is made for shifting the datum for the measurement to any point along the traverse of the slide. Adjusting knobs are incorporated so that the operator can obtain a coincidence reading on the meter when the dials are set to zero, but with the slide set to any position.

A machine which has been equipped with the system is shown in Fig. 4. This is a Kearns No. 0 planer-table type horizontal boring machine installed at the Leicester factory of the British United Shoe Machinery Co., Ltd., the work being carried out in close co-operation with H. W. Kearns & Co., Ltd.* The sliding movements of the machine have traverses of 57 in. horizontal and 42 in. vertically, and the slides may be set up to any position by setting up the co-ordinates on the operator's control desk. The dialling procedure is suitable for very short production runs and tool-room work. For longer runs, the slides can be set up by a card reader, also incorporated in the control desk. One punched card per hole centre is employed, so that instructions for the operator can be added where appropriate, and a stack of cards must be prepared for each workpiece. Provision is made for automatically clamping the slides when the desired co-ordinate position is reached.

The information given on the drawing or print consists of dimensions with respect to two convenient datum lines, but to simplify setting up, means are provided for quickly changing the datum of measurement of each traverse.

*"Horizontal Boring Machine Equipped for Automatic Co-ordinate Setting," *Machinery*, Vol. 88, page 519.

Wide speed range servo-mechanisms necessary for the co-ordinate setting provide convenient feed drives for milling operations, and suitable controls for this purpose are fitted.

The card-reader unit moves the hand-setting dials through the required amounts, thereby affording a means of checking, when necessary, the accuracy of the card reading. Identical servo-systems are used for both traverses, but for purposes of describing the system only one of these will be considered in connection with the diagram in Fig. 5.

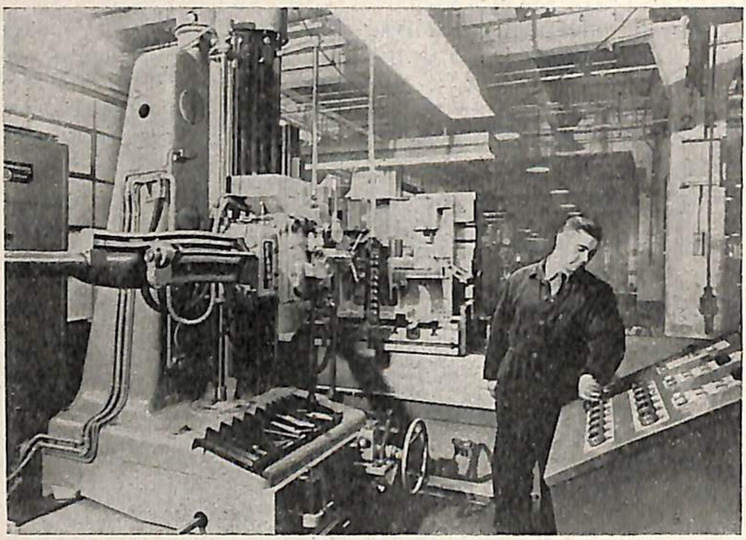


Fig. 4. General View of the Kearns No. 0 Planer-table Type Horizontal Boring Machine equipped with the British Thomson-Houston Automatic Co-ordinate Setting System

When the required co-ordinate dimension has been set up on the six dials, the input synchros S_1, S_2, S_3 and S_4 are rotated through suitable gearing to give misalignment signals in co-operation with the corresponding output synchros T_1, T_2, T_3 and T_4. The decimal dimensions are defined by the shaft rotations of S_2, S_3 and S_4 which cause the servo-amplifier A to operate the motor M, until the S_2-T_2, S_3-T_3, and S_4-T_4 are in alignment. High-quality instrument gearing and an accurate micrometer screw shift the electromagnetic unit through the required decimal dimension. The integral part of the dimension, with a contribution from the decimal part, is represented by a rotation of the synchro S_1 which is interconnected with the synchro T_1 geared to the leadscrew. A misalignment signal from S_1-T_1 controls the servo-amplifier C and, by means of the motor M_2, brings the table to within about 0·2 in. of the desired position, the traverse speed being maintained at approximately 120 in. per min. until the last inch or so of travel

is reached, after which the speed is progressively reduced. Control of the motor M_2 is now transferred, by way of the servo-amplifier B, to the electro-magnetic head. The control signal from the latter controls the rotation of the motor M_2 until the poles of the magnetic head are aligned opposite the nearest hole in the bar, whereupon the error signal from the magnetic head becomes zero.

During the approach to alignment under the control of the electro magnetic head, a temporary misalignment signal is injected into the amplifier B, so that the table travels to a "false alignment position," approximately 0·020 in. from the true alignment. The temporary signal

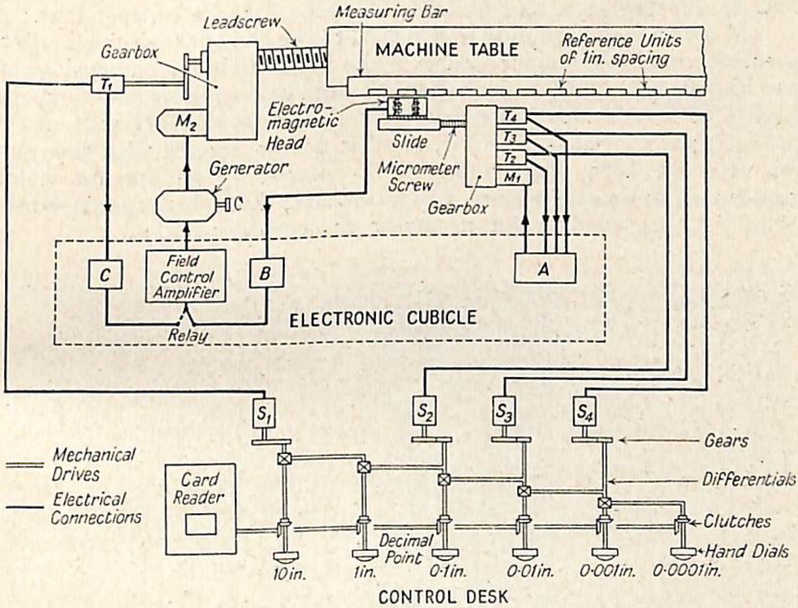


Fig. 5. Diagram showing the Arrangement of the B.T.H. System as fitted to the Kearns Boring Machine

is then automatically removed so that the final approach to alignment is always from the same direction. The error signal from the magnetic head is proportional to the displacement from the desired position, and reverses in phase for an error in the opposite direction. Consequently, the final approach to alignment is made under conditions of controlled velocity and retardation of the table, so that the manner of stopping is predetermined by the electronic circuits, and not by extraneous conditions such as the viscosity of lubricants or the loading of the table.

Referring again to Fig. 5, it will be seen that the synchros S_1, S_2, etc., are not operated directly by the dials, but through differential and other gearing. The differentials serve to add one-tenth of the rotation

of any dial to that of the shaft behind the adjacent dial on its left-hand side. This is necessary for the following reasons:—

(a) In the coarse, fine and very fine data transmission between the desk and the micrometer servo, there is a fixed relationship between the rotors of T_2, T_3, and T_4 through a normal gear train. The same apparent relationship must, therefore, hold between the shafts of S_2, S_3, and S_4, in order that alignment S_2 to T_2, S_3 to T_3, and S_4 to T_4 may take place simultaneously and unambiguously wherever the dials are set. It would not be satisfactory to gear the dial together directly, since, with such an arrangement, the right-hand dial would have to make 1,000 revolutions for every 1 in. change of setting; it is preferable that, to the operator, the dials should appear to be independent.

(b) Differential coupling is also used to the left of the decimal point, to ensure that no ambiguity arises if the input dials are changed from, say, 12.0000 to 12.9999. This change would cause the electro-magnetic head to be moved very nearly into alignment with the 13th unit on the measuring bar. Since, however, it must not be aligned with this unit but with the 12th, the synchro S_1 is rotated by an amount which corresponds approximately to 0·9999 in., and through the main servo-motor M_2, brings the table nearly to the correct position.

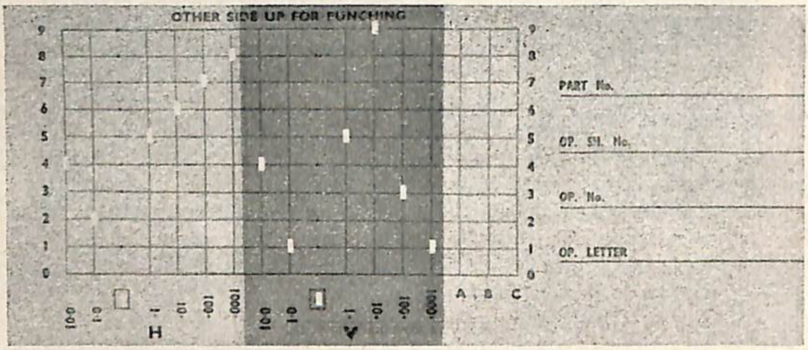


Fig. 6. Punched Card of the B.T.H. System prepared for a Horizontal Co-ordinate of 42.5678 in. and a Vertical Co-ordinate of 41.5931 in.

For the card method of setting, standard size business-machine cards are used, made of a material impervious to oil. They can be prepared by means of a simple hand punch, one card being used for each pair of co-ordinates. A typical card is shown in Fig. 6.

In operation, a card is taken from the stack and placed on the card carriage. On depression of a push button, the carriage with the card is withdrawn into the reader, and simultaneously the dials are automatically returned to their zero positions. The carriage then reverses its direction of movement and brush contacts are lowered on to the card. As the card is returned to its starting position, the dials rotate in unison. The brushes can complete electrical circuits

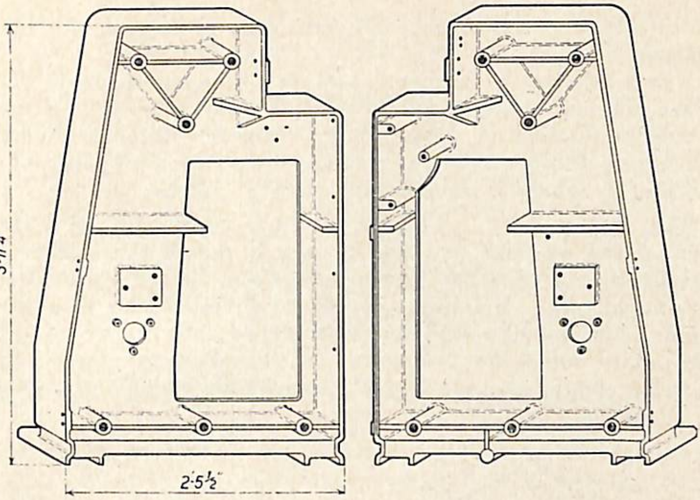


Fig. 7. Examples of Workpieces on which important Savings have been made by the use of the B.T.H. System on the Kearns Machine

through the holes in the card and when any one brush makes contact, the appropriate dial is disengaged from the driving mechanism and is left accurately positioned by means of a detent wheel and spring-loaded arm.

In addition to the automatic co-ordinate setting, milling feeds are available, and advantage is taken of the servo-system to provide continuous adjustment of feeds from ½ to 10 in. per minute.

The accuracy required from the installation is $\pm$ 0·0005 in., but $\pm$ 0·0002 in. can be achieved. By using very accurate micrometer screws for positioning the detector heads, and by taking advantage of the facility for fine adjustment of the 1 in. units on the measuring bar, the equipment is capable of operating to $\pm$ 0·0001 in.

Some idea of the comparative machining times which are being obtained may be gained by reference to Fig. 7. In the side frame seen at the left, 6 holes are drilled and counterbored, 9 holes are drilled and tapped, and 11 holes are drilled. Previously, the time required for marking out and drilling was 4 hrs. 34 min., and this has been reduced to 2 hrs. 17 min. The side frame at the right requires the following operations: 9 holes drilled and counterbored; 7 holes drilled and tapped; and 8 holes drilled and spot-faced. In this instance, the time has been reduced from 4 hrs. 47 min. (including marking out) to 2 hrs. 34 min.

The Ferranti System.* This control system can be divided into three stages. Firstly, the transfer of information from drawings and other sources on to punched paper tape; secondly, the production of a magnetic tape from the paper record by means of a digital computer;

*"Automatic Control of Machine Tools," D. T. N. Williamson, *Machinery*, Vol. 84, page 1210.

and, thirdly, the use of the magnetic tape to control the machining operation.

The workpiece is designed and the drawing made in the usual manner, the only departure from normal practice being concerned with the precise method of dimensioning, whereby all measurements are given from a datum and includes the co-ordinates of all points of change, for example, where a straight line joins a circular arc.

THE PAPER TAPE. A planner who is conversant with the capabilities of the machine and the manner in which the workpiece is to be produced transfers the dimensional data, in the correct sequence, to the paper tape. For this, a keyboard devise similar to a typewriter is used. Also incorporated in the punched tape is information such as the cutter radius, the feed rate, and the rotational speed. In Fig. 8 is shown a simple example of profile-machining capable of reproduction

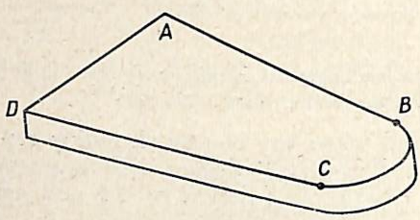


Fig. 8. Example of a two-dimensional Profile showing the Critical Co-ordinate Points

by the system. For this, the x and y co-ordinates of the points A, B, C, and D would be given from some datum point, which could be the point A on the line AD. Also, between each pair of points, the type of line or curve would be specified, which in the present example would be: AB, a straight line; BC, a circular arc; CD, a straight line; and DA, another straight line.

For a non-linear contour that can be expressed by an equation or parametric quantities, no co-ordinates would be required; thus for the circle, merely the centre and radius are required. The types of curve which are covered are limited only by the complexity of the associated computer, but, in practice it is expected that the computer will be able to cope with any second-degree curve such as circles, ellipses and parabolæ. More complex shapes can be approximated with sufficient practical accuracy by a combination of such curves.

For the aircraft industry, it may be necessary for the computer to deal with fourth-degree equations to enable aerofoil surfaces to be machined.

THE COMPUTER. When the paper tape leaves the planner, it contains the minimum amount of information required to produce the component, but before the component can be machined, this information must be extended, with the incorporation of data for the control of contours between the co-ordinate points. These data are determined by the digital computer, which accepts the basic information and,

controlled by the equations of the curves, calculates continuously the required path of the axis of the cutting tool in terms of the x, y and z co-ordinates.

The output in each co-ordinate direction is in the form of a train of electrical impulses, each pulse corresponding to a very small unit of movement, which in practice is 0·0001-inch. The total number of pulses in each channel determines the distance moved, and the frequency of the pulses determines the speed of movement or feed rate. The pulses are synchronized in such a manner that a tool thus controlled follows a path corresponding to the calculated track within 0·0001-inch. These pulses are recorded on three separate channels on magnetic tape. A fourth channel on the same tape is simultaneously recorded, and this incorporated control information pertaining to functions of the machine other than slide movements.

Since a modern digital computer can handle information at a much higher rate than that of the greatest feed rate employed, advantage is taken to record the pulses on magnetic tape moving at ten times the normal play-back speed. The same computer can therefore be used to record tapes for a comparatively large number of machines. The paper tapes, being prepared by a number of planners, do not occupy computer time, and the number of machines controlled depends on only computer speed and the average duplication rate. With a computer-speed/machining-speed ratio of ten, and an average duplication rate of five, a single computer could supply fifty machines with recorded tapes. It is estimated that the duplication rate would vary from unity for single prototypes and tools to ten or twenty for component parts. In addition, the use of a tape recording allows the amount of electronic equipment in the workshop to be reduced to a minimum.

Control of Machine. A digital computer can provide control information to any desired degree of accuracy, but this is of no value unless the measurement and control system of the machine provides a similar degree of accuracy. It was clear at the outset of the Ferranti research programme on the subject that no great reliance could be placed on the use of a leadscrew as a method of measurement, although this is frequently the only measuring agent fitted to the machine. Problems of back-lash and the compressibility of the oil film render such a system useless where machining must be taken to close tolerances by dead reckoning.

A method of measurement was devised which utilizes an optical grating with a specified number of lines per inch. This method has the advantage that the accuracy is unaffected by wear and can be made as high as desired. For instance, with a grating of 30,000 lines per inch, it would be possible to discriminate between a few millionths of an inch, providing, of course, that attention were paid to all other factors which affect fine measurement, such as temperature, vibration, and slide design. However, by the use of gratings with 5,000 lines per inch, it is a simple matter to move a slide consistently to an accuracy of 0·0001-inch, which is sufficiently precise for the majority of conventional engineering purposes.

Both photographic and prismatic gratings can be used for this purpose, but prismatic gratings have definite advantages when the number of lines exceeds about 1,000 per inch. A method adopted for using the gratings for measurement is indicated in Fig. 9. A suitable length of grating is attached to the machine slide, and a short length of the same grating is attached to the corresponding slideway, so that one grating traverses the other with the two surfaces almost in contact. If a beam of light be projected through a pair of gratings suitably aligned, the Moiré fringe pattern produced will modulate the light

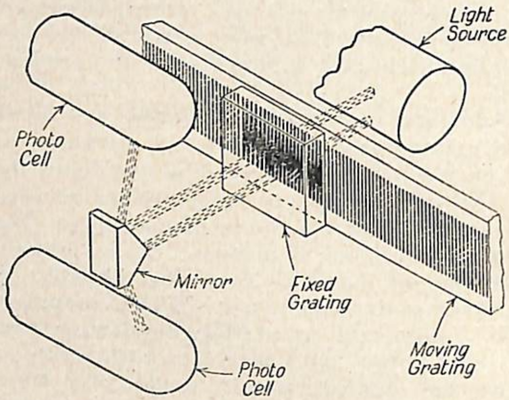


Fig. 9. Diagram showing how, in the Ferranti System, use is made of a Pair of Optical Gratings to detect Movement of the Machine Element

transmission when there is relative movement. One complete cycle of variation of intensity will occur for a movement equal to the pitch of the grating, and from this variation, two discrete electrical impulses per grating line can readily be obtained. By arranging two photocells so that the phases of this light variation differ therein, a two-phase electrical system can be formed the direction of the phase rotation corresponding to the direction of movement of the slide.

The servo-mechanism which controls the table movement is so arranged that, on receiving the command signal, the table moves in the appropriate direction until a pulse from the grating cancels the command pulse. Thus, if a train of impulses is received, the slide is moved at a rate such that a similar train, lagging with respect to the first by an amount not exceeding one pulse, is produced. In this way, the error can not exceed one ten-thousandth of an inch, unless the servo-mechanism is overloaded.

APPLICATION TO MILLING MACHINE CONTROL.* A machine to which the Ferranti system has been applied is the C.V.A.-Kearney and Trecker No. 2E knee-type vertical milling machine shown in Fig. 10, with the incorporation of magnetic tape control. This machine is equipped for servo-control of the spindle quill, and the longitudinal

*"Developments in the Ferranti System of Magnetic Tape Control for Machine Tools," *Machinery*, Vol. 88, page 451.

and transverse motions of the table, so that 3-dimensional milling can be performed

The previously fitted Acme-thread feed screws and nuts for the table and the cross-slide have been replaced by circulating-ball nuts and screws to ensure easy movement under conditions of preloading for the elimination of backlash. The absence of backlash is essential for the satisfactory operation of a servo-system, and a sensitive movement ensured the best possible use of the available servo-power. Whereas the cost of a motor for the normal feed purposes is not usually of much

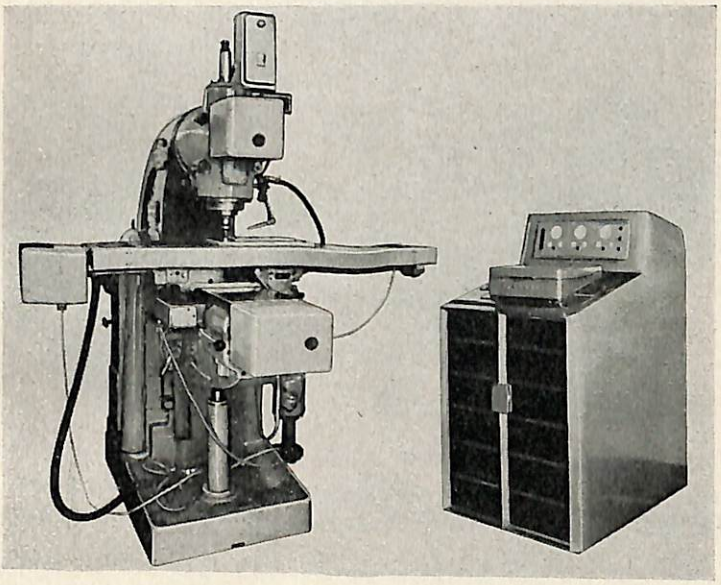


Fig. 10. The C.V.A.-Kearny and Trecker Vertical Milling Machine fitted with Ferranti Three-dimensional Magnetic-tape Control

consequence, servo-motors are relatively expensive, and the performance of a servo-mechanism is inherently reduced as the size of the unit is increased.

Backlash elimination is accomplished by the use of two nuts, one of which is fixed, and the other arranged to slide axially. A load of 500 lb., which is in excess of any feed pressure likely to be encountered, is applied between the two nuts by means of a compression spring. No alteration is made to the bearings of the two feed screws, or to the table and the cross-slide guideways. It has been stated that the efficiency of the transmission has been increased from 20 to 80 per cent by this method.

The servo-motor and gearbox units are of $\frac{1}{2}$-h.p. capacity. To minimise the effects of any variation in the normal mains supply, the servo-motors are designed to operate on 115 volts, 3-phase, 400 cycles,

with a maximum speed of 10,000 r.p.m. Magnetic drum brakes are fitted to lock the machine slides when the motor is de-energized, or when the limits of slide travel are reached.

Special attention has been paid in the design of the gearboxes to provide for a smooth drive, with a minimum of friction and an entire freedom from backlash. A standard gearbox having a ratio of approximately 84 to 1 has been developed, and this, at the maximum servo-motor speed of 10,000 r.p.m., provides a feed rate of 30 in. per min. when coupled to a $\frac{1}{4}$-in. pitch leadscrew. The shafts are mounted in needle bearings, or, where they are subjected to end thrust, in taper roller bearings.

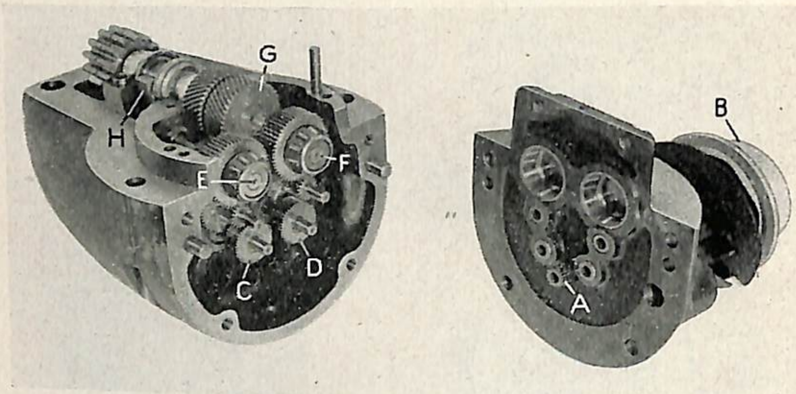


Fig. 11. Servo-motor and Gearbox Unit, partially dismantled, which has been developed for Controlling the Spindle-quill Movement on the Machine shown in Fig. 10

Provision is made for the output shaft to drive in three alternative planes, so that the gearbox can be mounted in the most suitable position on the machine. Connection to the feed-screw of the machine is effected through a self-aligning coupling which incorporates torque-limiting features to safeguard the box against overload.

The gear box and servo-motor which have been specially designed for controlling the spindle-quill movement of the machine are shown partially dismantled in Fig. 11. The elimination of backlash has been accomplished by the use of a double gear train in conjunction with an axially loaded, double helical gear in the final drive. The pinion *A* of the servo-motor *B* meshes with the two spur gears *C* and *D* comprising the first stages of two 4-step reduction trains, arranged in parallel. The final drive pinions on the shafts *E* and *F* have single helical teeth of opposite hand, and mesh with the double-helical gear *G* on the output shaft which is spring-loaded axially through a pivoted yoke *H*. Taper roller bearings are provided on the shafts of the gears *E* and *F* to take the end thrust, and needle roller bearings are fitted for the spur gear shafts.

The measuring equipment associated with the machine table movement is shown in Fig. 12 with the cover removed. At *A* is the long diffraction grating attached to the machine table, and *B* is the unit which is fastened to the cross saddle. This houses the short grating, the photo-electric cells and the light source. Particular care has to be taken to prevent the ingress of swarf and coolant to the system. Since the unit *B* is fixed and enters the casing over the table grating, it has been necessary to provide a running seal, which consists of a

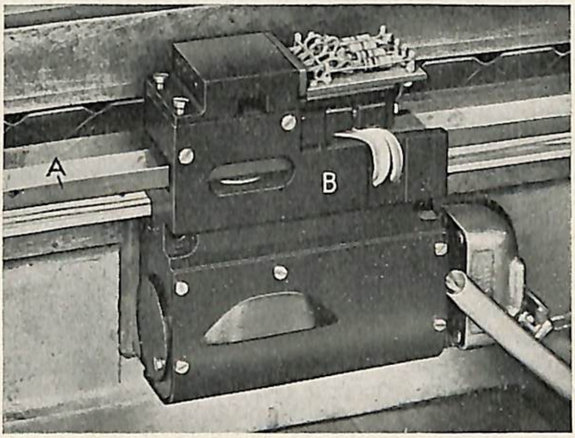


Fig. 12. Close-up View of the Diffraction-grating System for the Table of the Milling Machine

flexible band, 0·0025-in. thick, attached to the optical unit and arranged to wind on and off spools at each end of the table. The edges of the band run between Neoprene sealing strips attached to the lower edges of the cover.

The Ferranti measuring system has the advantage that it is entirely free from friction and wear, and can be installed in close proximity to the part which is to be machined. Moreover, since information is obtained from a relatively large area of grating, the interference pattern being an integration of a large number of intersections, the lengths of grating can be placed end to end, with small gaps if necessary. The absence of a few lines merely lowers the contrast of the pattern by a corresponding amount.

Diffraction gratings for the purpose described are, at the time of writing, in lengths of 3 ft., but longer gratings are expected to be provided. The gratings have been made available by the National Physical Laboratory, and Ferranti Ltd. hold patents in connection with the application of the gratings in a measuring system.

Gratings in use have 500, 2,500 and 5,000 lines per inch, enabling measurement to be made to accuracies of 0·001, 0·0002 and 0·0001 in., respectively.

The control unit is seen on the right in Fig. 10. It incorporates the multi-channel tape reader, the magnetic amplifiers for supplying the servo-motors and other associated equipment, and has been specially designed to withstand workshop conditions, being pressurized by filtered air to prevent the ingress of dust. Electrical maintenance is facilitated by a system of plug-in circuit cards which can be readily removed from their trays and replaced by others in the event of a fault developing.

The circuits have been designed so that all the components, including valves, can change their characteristics by 30 per cent, simultaneously, in the worst direction, before there is an adverse effect on the operation of the equipment.

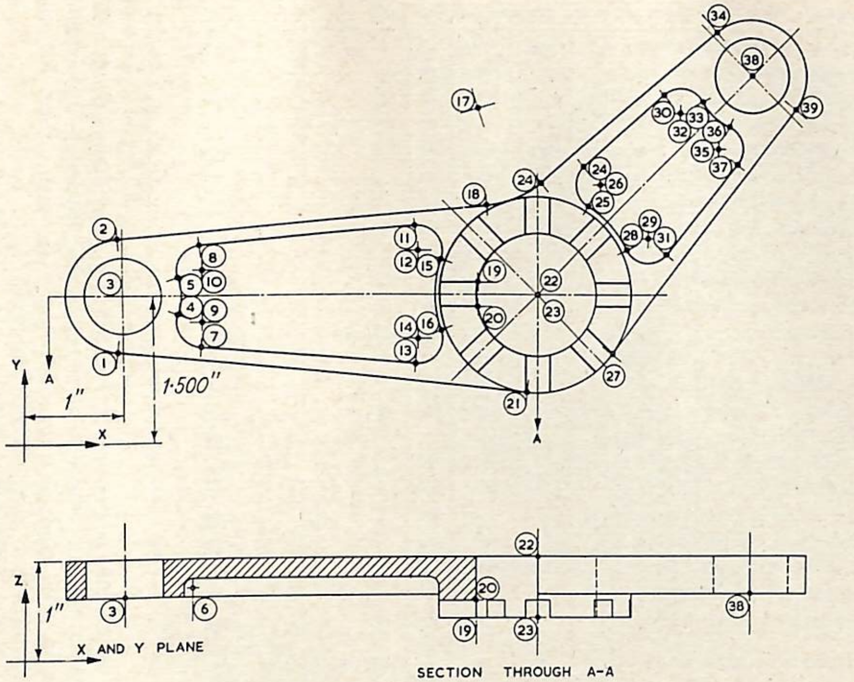
The system functions as follows: Assume that there are three control channels, x, y and z, and that a fourth is added for checking purposes. When the magnetic tape is being prepared on the computer, pulse train is recorded on this fourth channel, the number of pulses on which is equal to the algebraic sum of the pulses on the x, y and z channels divided by four. Circuits are included in the machine control unit which summate the pulses received from the x, y and z measuring systems on the machine tool, and check that this algebraic sum divided by four corresponds to the pulse train on the fourth channel.

Any fault, such as tape damage, incorrect reading, or failure in the electrical circuits is detected, and protective gear operated, should the cumulative discrepancy exceed predetermined limits, to stop and brake the servo-motors, so that the machine slides are instantly brought to rest.

Practical Application. In preparing a drawing for a component to be produced on the tape-controlled machine, the various dimensions are specified from x, y, and z axes as shown by the example of Fig. 13, and it is stipulated that the origin of co-ordinates shall not be within the workpiece, in order to avoid negative values. Also, all dimensions must be expressed in decimal fractions. The points of change from one curve or straight line to the next are specified, and a table is prepared as shown, giving the co-ordinates of these points. For the sake of clarity, only three dimensions are given on the actual drawing.

From the drawing, and from information concerning the cutter diameter and feed rate to be used, a planning sheet, Fig. 14, is prepared.

The first operation in producing the lever component is to machine the profile from the point 1 through 21, 27, 39, 34, 24, 18, 2, and back to 1. The first cut from 1 to 21 is a straight line, and no entry is made under the columns "plain of curve" and "type of curve" of the planning sheet. The position of point is entered along the first line of the sheet, with the x, y and z co-ordinates against the designations COX, COY, and COZ respectively. This procedure is repeated for the point 21. Between the points 21 and 27, a circular arc is required, and to define the direction of rotation the letters YAX are inserted in the column "plane of curve", and under "type of curve" the letters CIR are written. The co-ordinates of the centre of the circular arc are placed under "co-ordinates of pole of curve" against POX, etc.



CHANGE POINTS	X CO-ORD	Y CO-ORD	Z CO-ORD
1	0·942	0·941	1·000
2	0·955	2·061	1·000
3	1·000	1·500	0·625
4	1·534	1·323	0·625
5	1·538	1·665	0·625
6	1·656	1·500	0·719
7	1·749	0·995	0·625
8	1·760	1·988	0·625
9	1·771	1·244	0·813
10	1·777	1·739	0·813
11	3·979	2·134	0·625
12	3·995	1·884	0·813
13	3·997	0·795	0·625
14	4·019	1·044	0·813
15	4·234	1·811	0·625
16	4·254	1·131	0·625
17	4·485	3·348	—
18	4·565	2·351	1·000
19	4·638	1·625	0·563
20	4·638	1·375	0·563
21	5·147	0·505	1·000
22	5·250	1·500	1·000
23	5·250	1·500	0·375
24	5·107	2·565	0·625
25	5·760	2·432	0·625
26	5·880	2·652	0·813
27	6·048	0·897	1·000
28	6·202	1·971	0·625
29	6·426	2·082	0·813
30	6·612	3·583	0·625
31	6·623	1·928	0·625
32	6·771	3·390	0·813
33	6·996	3·501	0·625
34	7·150	4·190	1·000
35	7·159	3·013	0·813
36	7·264	3·239	0·625
37	7·355	2·858	0·625
38	7·500	3·750	0·625
39	7·949	3·411	1·000

Fig. 13. Method of marking the Change Points and compiling a Table of Co-ordinates for a Lever Component in the Application of the Ferranti System

INITIAL SIGNAL	TYPE OF MESSAGE	DATUM CO-ORD. OF X	DATUM CO-ORD. OF Y	DATUM CO-ORD. OF Z	CUTTER FEED RATE		CUTTER DIAMETER		COMPENSATION SENSE	END OF LINE
STA-	NMC-	DAX-	DAY-	DAZ-	RAT-	005	DIA-0	750	TDC-1	*

SPECIAL INSTRUCTIONS

STANDARD MESSAGES

TYPE OF MESSAGE	TYPE OF CODE	INSTRUCTIONS	END OF LINE	TYPE OF MESSAGE	PLANE OF CURVE	TYPE OF CURVE	CO-ORDINATES OF CHANGE POINTS									CO-ORDINATES OF POLE OR CURVE						
NMC-	-		*	SMC-	-	-	COX-	000	942	COY-	000	947	COZ-	001	000	POX-			POY-			POZ-
NMC-	-		*	SMC-	-	-	COX-	005	147	COY-	000	505	COZ-			POX-			POY-			POZ-
NMC-	-		*	SMC-	YAX -	CIR -	COX-	006	048	COY-	000	897	COZ-			POX-	005	250	POY-	001	500	POZ-
NMC-	-		*	SMC-	-	-	COX-	007	949	COY-	003	411	COZ-			POX-			POY-			POZ-
NMC-	-		*	SMC-	YAX -	CIR -	COX-	007	150	COY-	004	190	COZ-			POX-	007	500	POY-	003	750	POZ-
NMC-	-		*	SMC-	-	-	COX-	005	107	COY-	002	565	COZ-			POX-			POY-			POZ-
NMC-	-		*	SMC-	XAY -	CIR -	COX-	004	565	COY-	002	351	COZ-			POX-	004	485	POY-	003	348	POZ-
NMC-	-		*	SMC-	-	-	COX-	000	955	COY-	002	061	COZ-			POX-			POY-			POZ-
NMC-	-		*	SMC-	YAX -	CIR -	COX-	000	942	COY-	000	941	COZ-			POX-	001	000	POY-	001	500	POZ-
NMC-	-		*	SMC-	-	-	COX-	000	000	COY-	000	000	COZ-	000	000	POX-			POY-			POZ-
NMC-	-	STO-	*	SMC-	-	-	COX-			COY-			COZ-			POX-			POY-			POZ-
NMC-	-	RAT-005	*	SMC-	-	-	COX-			COY-	001	250	COZ-	000	625	POX-			POY-			POZ-
NMC-	-		*	SMC-	-	-	COX-	003	997	COY-	000	875	COZ-			POX-			POY-			POZ-
NMC-	-		*	SMC-	XAY -	CIR -	COX-	003	850	COY-	001	500	COZ-			POX-	005	250	POY-	001	500	POZ-
NMC-	-		*	SMC-	-	-	COX-	000	000	COY-			COZ-			POX-			POY-			POZ-
NMC-	-		*	SMC-	-	-	COX-			COY-	001	750	COZ-			POX-			POY-			POZ-
NMC-	-		*	SMC-	-	-	COX-	004	025	COY-	002	125	COZ-			POX-			POY-			POZ-
NMC-	-		*	SMC-	YAX -	CIR -	COX-	004	025	COY-	002	125	COZ-			POX-	005	250	POY-	001	500	POZ-
NMC-	-		*	SMC-	XAY -	CIR -	COX-	005	674	COY-	002	808	COZ-			POX-	005	250	POY-	001	500	POZ-
NMC-	-		*	SMC-	-	-	COX-	008	073	COY-	004	677	COZ-			POX-			POY-			POZ-
NMC-	-		*	SMC-	-	-	COX-	008	250	COY-	004	500	COZ-			POX-			POY-			POZ-
NMC-	-		*	SMC-	-	-	COX-	006	239	COY-	002	489	COZ-			POX-			POY-			POZ-
NMC-	-		*	SMC-	XAY -	CIR -	COX-	006	578	COY-	001	944	COZ-			POX-	005	250	POY-	001	500	POZ-

Fig. 14. Part of the Planning Sheet for the Lever, from which the Paper Tape is punched on a Teleprinter Keyboard

Every movement necessary to specify the part is thus dealt with, and feed rates can be altered as required by inserting appropriate instructions in the column provided, together with stops for tool changing or any other relevant information.

Curves such as ellipses, parabolæ and hyperbolæ can be directly specified by means of a symbol, and curves which cannot be so specified are expressed in terms of running co-ordinates. These, with suitable instructions, enable the computer to produce a smooth curve.

From the planning sheet, the punched paper tape is produced, a procedure which requires only copy-typing on a teleprinter. Simultaneously, the figures and letters are printed on a sheet of paper for checking purposes. For the planning sheet shown in Fig. 14, the first line to be tapped on the teleprinter would be: SMC-COX-000942-COY-000941-COZ-00100-SLO. The symbol SLO appears in a "control of rate" column not shown in Fig. 14. Columns for gradient-multiplying constants in the three co-ordinate planes such as used for certain curves have also been omitted.

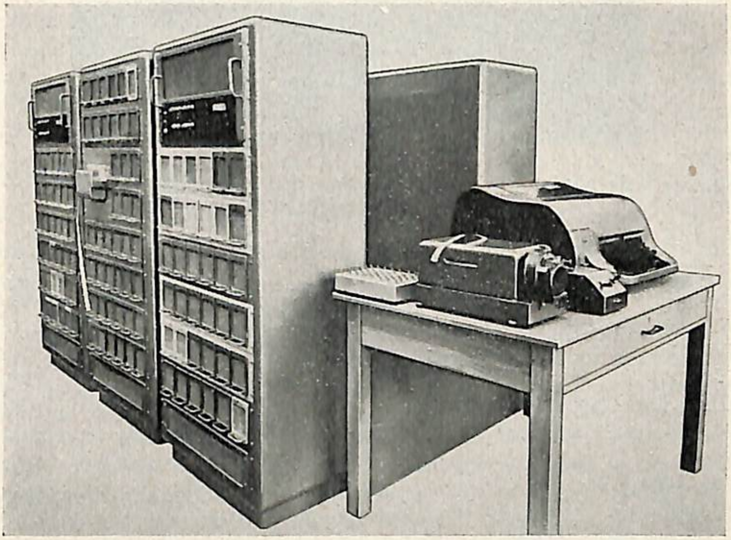


Fig. 15. The Computer and Teleprinter Keyboard for preparing punched Paper Tapes and Magnetic Tapes for the Ferranti System

The tape is punched to a binary code which is converted in the computer. The computer for producing the magnetic tape and the teleprinter on which the paper tape is punched are illustrated in Fig. 15. Tapes can be recorded eight times as fast as they can be played back on the control unit, so that one computer can serve a number of machine tools. Also, since workpieces are often required in batch quantities, it is anticipated that, on average, one computer should be able to provide tapes for about 50 machine tools.

For the control lever shown in Fig. 13, which is made from L40 aluminium alloy, the time taken to compile the planning sheet, punch the tape and prepare the magnetic tape on the computer was approximately one hour. Excluding tool changing, the machine operation took 35 min., but this could have been reduced to about 7 min. had a higher spindle speed been available on the machine. The time for a skilled machine operator to make the same component by conventional methods was 12 hours.

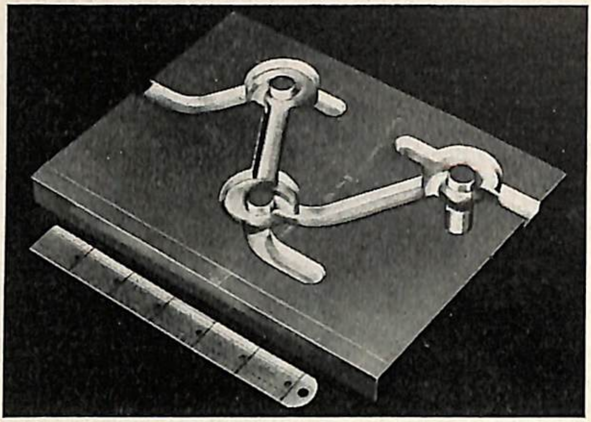


Fig. 16. A Light-alloy Wave-guide Component that was produced in Six Minutes on the Tape-controlled Milling Machine

Fig. 16 shows a light-alloy wave-guide member of complicated form which was machined at a single pass, in only 6 min., to an accuracy of 0·001 in. The width of the profile is 0·5 in. and the depth 0·25 in. Two of these members, one the mirror image of the other, are assembled together, face to face, to form a complete wave guide. The member of opposite hand is readily produced from the same magnetic tape by reversing the sense in one plane, this being effected by an adjustment on the control panel. Using conventional machining methods, the time taken to produce one of these members was about a week.

In setting up the workpiece on the machine table, it is only necessary to locate it in relation to the cutter, with reference to the datum point from which the co-ordinate dimensions are given. Machining can then proceed automatically under the control of the tape. The servo-mechanisms lock the pulse train coming from the diffraction grating to the command pulse coming from the tape, within an accuracy of one pulse.

It has been pointed out that although a very satisfactory performance can be obtained from a converted machine tool such as the milling machine just described, if full advantage is to be taken of the technique, machine tools specially designed for the purpose will be necessary, with built-in arrangements for taking advantage of the control channel on the magnetic tape whereby spindle starting and stopping, speed changing fixture operation and other functions can be controlled automatically during the cycle.

Mullard Precision Measurement System.* A system developed by Mullard Ltd., is designed primarily to reduce the time and skill required for initial setting-up operations for such work as drilling, boring and milling.

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The arrangements employed enable the associated machine member to be accurately set to predetermined dimensions, without the reading of closely-marked scales, verniers, or micrometers by the operator, the required dimensions being set-up on six 10-position dials. For example, if the machine table is required to be moved through a distance of 28·7605 ins., each digit of this number is individually set on a separate dial. The dials set-up switches so that the information is fed to an electronic counter. This unit differs from the conventional type in that it is reversible, and can, in consequence, be employed to add or subtract dimensional increments.

Movement of the table is measured by an optical system in units of 0·0001-inch. The counter automatically compares the actual position dimension of the table with the required setting dimension, the difference between the two values being indicated on a dial Thus, the dial indicates whether the distance moved by the table is too great or too small, and provides the operator with an approximate indication of the magnitude of the error. To facilitate reading, the dial calibrations are arranged to be very open near the zero position, so that the coincidence between the actual and the required dimensions is indicated by a null reading, which is visible from a distance of two or three feet.

The procedure for setting up a machine to an accuracy of 0·0001-inch may be divided into two stages; the dials of the six switches are set up to the necessary values; and the machine is adjusted until a null reading is obtained from the dial of the electronic counter.

As in all similar systems, one of the principal problems that must be overcome is associated with the measurement of the machine movements to the required degree of accuracy. In the Mullard system, a standard scale is employed, calibrated in increments of 0·1-inch, to a high degree of accuracy. This is employed for reference purposes, and has been designed so that it can be produced without difficulty in a tool-room, by a skilled craftsman. For the intermediate measurements, optical interpolation is adopted, the interpolating scale being produced comparatively easy by photographic methods. The standard consists of a long rod, on which is cut a screw thread of buttress form, having a pitch of 0·1-inch as may be seen at *B* in Fig. 17. A 90-deg. segment is machined away along the length of the bar to provide a true section of the thread in an axial plane. The vertical face of each tooth is then ground and lapped, to ensure that the vertical edge of each thread form is 0·1-inch from its neighbour, to an accuracy of 0·00005-inch. The rod is of hardened steel and is fitted to the moving member of the machine with which it has the same coefficient of thermal expansion.

INTERPOLATION SYSTEM. The basic principles of the interpolation developed by Mullard, Ltd., are best understood by referring to Fig. 18. A transparent scale *S*, 4-ins. long is provided with 1,000 equi-spaced vertical opaque bands 0·002-inch wide, which alternate with transparent bands of equal width. An image of the interpolating scale is formed by a lens *L*, across the teeth of the buttress scale, as may be seen in Fig. 17, while a typical setting of the two scales may be seen in Fig. 18.

In practice, the buttress scale is mounted on the moving member of the machine, and the optical image XY is fixed in space. In consequence, the distance traversed by the moving member can be readily determined from the relative position of the two scales. In Fig. 18, for example, the total displacement of the first datum edge A of the buttress scale is 0·2-inch plus the distance d between the edge C and the end of the interpolation scale Y. The number of bands between C and Y is the number of ten-thousandths of an inch in the distance d. The number of bands is counted by transmitting a line of light from the source Z, Fig. 17, through the interpolation scale S. the light source

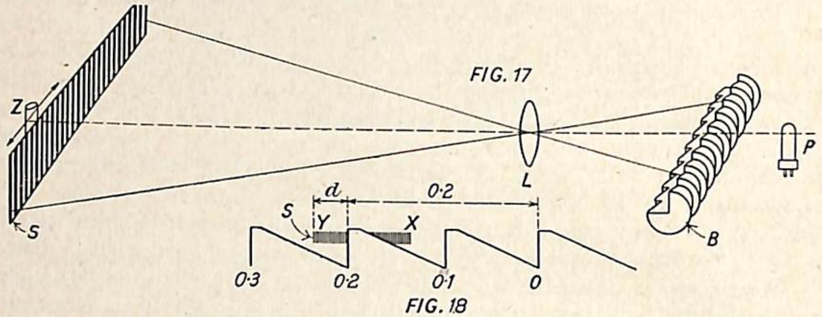

Fig. 17. Diagrammatic Representation of the Mechanical-optical Measuring System developed by Mullard, Ltd.

Fig. 18. The Disposition of the Buttress Scale and the Optical Image of the Interpolation Scale

being arranged to move behind the scale so that the transparent bands are illuminated progressively from X to Y. By this arrangement, a succession of light pulses are received by a photo-electric cell P, located close to, and behind the buttress scale.

As the moving light passes across the sloping edge of each buttress tooth, the pulses are reduced in amplitude and are finally completely interrupted. The sudden reappearance of the pulses when the light beam comes into line with the vertical edge of the buttress scale, as indicated at C, is employed as a signal to initiate the counting of the pulses by the associated electronic mechanism. Counting proceeds until the end of the interpolation scale Y is reached, the output count then corresponding to the fraction d in 0·0001-inch units.

The arrangement is such that the scale is scanned repeatedly by the line of light and the distance d is determined afresh at each scanning movement. In this way, an output signal is provided at regular intervals, which corresponds to the position of the moving member. At the end of each scanning movement, the position of this member is compared with the required dimension by means of the reversible electronic counter, the difference between the distance moved and the set dimension being displayed on the instrument dial. This difference value is retained until the end of the next scanning movement, when a fresh value is indicated. Since only whole numbers of interpolation-scale bands can be

counted the relative position of the fixed and moving members of the machine is given to within a definite limit, namely, 0·0001-inch. However, the distance in which the count changes is less than 0·0001-inch, and the moving machine-tool element can be set to this intermediate position with an even greater degree of accuracy. The interpolation system is used in conjunction with a coarse measuring arrangement, whereby the correct vertical edge of the buttress scale can be located within 0·05-inch of the desired setting.

Selsyns and their Application.* Certain systems of copy-machining are based on the use of Selsyns, whereby the various movements are regulated. Selsyns are similar in many respects to slip-ring induction motors, but have special characteristics so that, when two or more units are operated in conjunction, angular motion or torque can be transmitted from one Selsyn to another. Alternatively, a voltage may be generated in one unit to correspond to the angular displacement between its rotor and the rotors of the other units of the system.

Selsyns are made by The British Thomson-Houston Co., Ltd., Rugby, in a range of sizes and in various forms, with differing electrical characteristics, including general-purpose, precision, power, power-amplifier, differential and servo position-control types. All these machines have wound stators and wound rotors with slip-rings, power-amplifier units being also provided with commutators. The smaller units are intended for use on single-phase supplies, whereas the larger machines and the power Selsyns are generally operated from three-phase electrical systems, although, in certain circumstances, these units also may be supplied from single-phase sources of power.

With the smaller precision and general-purpose units, damping is effected by means of flywheels, but if damping is necessary on the larger units, or on power Selsyns, it is accomplished electrically by means of external resistances.

Conventional Selsyns, with appropriate windings and cylindrical rotors, can operate as induction motors at speeds determined by the supply frequency and the number of poles in the stator windings. When operating as Selsyns in the region of these speeds, the Selsyn-characteristics are very much reduced, and it should be arranged that the units do not operate at speeds exceeding 80 per cent of their induction-motor speeds. For example, on 50-cycle supplies, the speeds of 2- and 4-pole machines should not exceed 2,400 and 1,200 r.p.m. respectively.

APPLICATION TO CONTROL SYSTEMS. In its simplest form, a Selsyn system consists of transmitter and receiver units, with an electrical connection, which is analogous to an infinitely flexible shaft. Generally, both units are excited from an a.c. supply, and any movement of the rotor of the transmitter Selsyn is reproduced by the rotor of the receiver. As with a flexible shaft, there is always an angle of lag between the receiving and transmitting units, and this angle, although generally small at low values of torque, becomes larger as the transmitted torque

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is increased. One transmitter can be connected to several receivers, but, if this practice be adopted, the transmitting unit must be carefully selected so that its size is in the correct relationship to the number and size of the receivers.

General-purpose Selsyns are used when great accuracy of correspondence between the transmitter and receiver is not essential. The machines are designed for continuous operation, rather than for low frictional resistance. For more accurate response, precision Selsyns are employed. These units are similar in construction to the general-purpose types, except that the internal friction has been reduced to a minimum. In consequence, for low values of transmitted torque, the

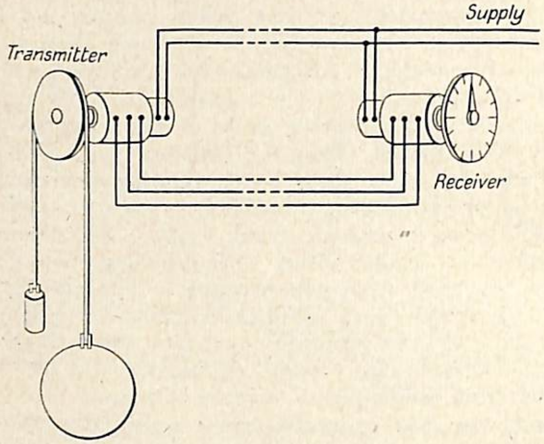

Fig. 19. Precision Selsyns employed for the Remote Indication of Liquid Level

angular difference between the transmitter and the receiver may be only one degree. The angle of lag will, of course, increase with any increase in load. A typical application of precision Selsyns is shown diagrammatically in Fig. 19, where units are employed to indicate at a distance the level of the liquid in a reservoir.

Although similar in design to the smaller general-purpose types, the power types are usually built into frames and end-shields of industrial slip-ring motors. These units are designed to ensure synchronous rotation of two or more mechanisms, the angular displacement varying with the transmitted load. In this respect they are similar in operation to the general-purpose units, although power Selsyns normally transmit torques of much greater magnitude. A typical application of power units is afforded by the synchronization of two conveyors, where one belt feeds material on to the other.

In a conventional Selsyn system, the torque generated by the receiver is equal to the torque applied to the transmitter, minus any losses in the system.

When it is necessary to operate a third Selsyn in response to the difference in position of two transmitter units, a differential Selsyn is incorporated in the circuit. The two transmitters are excited in the

usual manner, and there is electrical connection from each unit to the differential unit, which indicates the relative angular displacement of transmitters, and rotates at a speed which is the sum, or difference, of their speeds. Alternatively, it is possible to cause the two transmitter-shafts to rotate at predetermined speeds, the difference between these speeds being controlled by the speed of the differential Selsyn.

A differential type may also be arranged to actuate the electrical controls of an associated machine driving one Selsyn, so that the speed-differential between this unit and another may be maintained at zero.

SERVO POSITION-CONTROL SELSYNS. These are usually small units and are used to control servo-systems to a high degree of accuracy. Three types are generally available, namely, transmitter (energized), transformer (pick-up), and dual-purpose, transmitter-control transformer types.

In a conventional control arrangement, there is either a transmitter and a transformer unit, or two dual-purpose Selsyns, coupled to two shafts, the relative angular movement of which is required to very

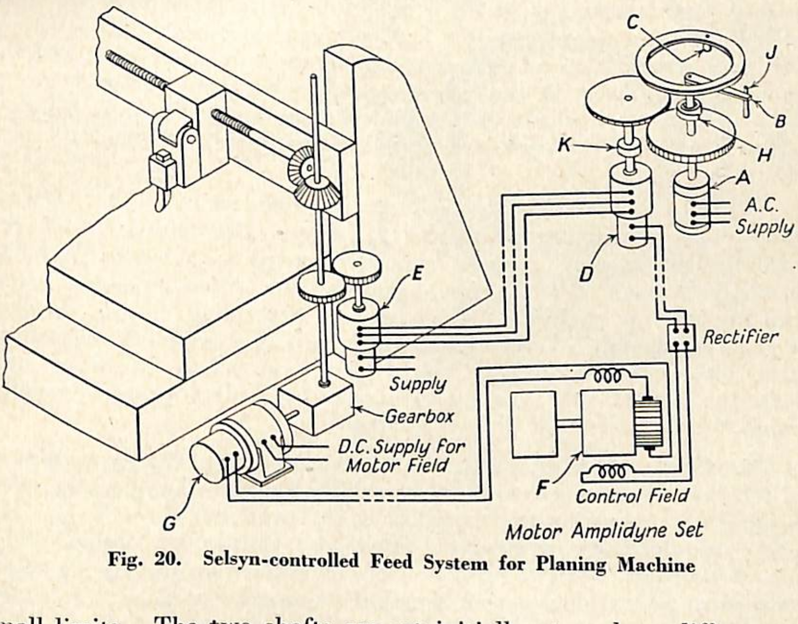

Fig. 20. Selsyn-controlled Feed System for Planing Machine

small limits. The two shafts are set initially at a phase difference of 90 deg. to each other, and no voltage is generated in the transformer unit when the relative displacement from this position is zero. If an angular displacement occur, a voltage is generated in the transformer Selsyn, which is amplified and employed to restore coincidence of the shafts by a suitable servo-mechanism.

An application of servo-position-control Selsyns to a planing machine is shown diagrammatically in Fig. 20; where these units are

employed to regulate the feed of the tool. The feed is engaged by the energizing of the torque-motor *A* when the planer reversing switch is tripped into the "cut" position. The motor shaft, with its arm *B*, continues to rotate until the arm contacts the adjustable stop *C*. As a result, the transformer Selsyn, (type P), indicated at *D*, is turned out of electrical alignment with the transmitter Selsyn (type E) indicated by *E*. In consequence, an electrical signal is generated which causes the amplidyne unit *F* to supply power to the d.c. driving motor *G*, until the latter, through associated gearing, has traversed the tool, and rotated the Selsyn *E*, so that electrical alignment is restored.

When the reversing switch is tripped into the return position, the torque motor is de-energized and the arm *B* is returned by the spiral spring *H*, until it contacts the fixed stop *J*. The provision of the freewheel *K* in the mechanism driving the Selsyn *D* ensures that the latter unit does not rotate during the reversal of the torque-motor.

Winding and constructional errors in the servo position-control units give rise to static errors of the order of one-fifth of a degree, measured at the Selsyn shaft. By the use of coarse and fine transmission, this component of error may be appreciably reduced when measured at the output shaft. Account must be taken, however, of additional errors, such as those caused by mechanical gearing and the dynamic inaccuracies in the whole system. In general, the accuracy of the system as a whole will be determined by mechanical rigidity, gearing errors, and the back-lash associated with the controlled mechanism.

Coarse and Fine Control.—In certain mechanisms, where extreme accuracy of coincidence is necessary, beyond the sensitivity of the normal Selsyn, recourse may be made to gearing up a Selsyn from the main drive. Such an arrangement suffers from the disadvantage that there are several positions of coincidence, depending on the ratio of the gears employed. A direct-driven Selsyn is also employed, therefore, which discriminates between the various coincident positions and selects the correct one. An arrangement of this description is usually termed " coarse and fine Selsyn control."

The Hilger & Watts Digitiser.* Developed by Hilger & Watts, Ltd., is a device called a digitiser which enables the position of a mechanism or machine tool member to be expressed directly in, say, inches and decimals of an inch, from any convenient datum. The basis of the digitiser is a form of circular scale specially divided and engraved to give a binary-scale signal of its angular position. In other words, the scale is so graduated that the electrical signals received from it by means of brush pick-ups in the case of metal scales, or photo-electric cells in the case of glass scales, are expressed in a numerical system of which digits are arranged in powers of two, and not in powers of ten as in the common arithmetical system. Thus only two effective digits, or discrete signals are required, which, numerically,

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may be expressed by "0" and "1," and these are easily transmitted electrically by a simple on-and-off device.

In this system, the number "9" would be expressed as 1001, which, on a circularly engraved scale, could be represented by a radial opaque patch one unit in length followed by a clear portion equal to two units in length, and a further opaque portion one unit in length. To pick up this number would require four brushes or the same number of miniature photo-cells, one for each digit or each digit-track on the scale. An example of the engraved pattern for a binary scale for use in a digitiser is shown in Fig. 21.

From the pick-ups, the signals are conveyed to a decoder, which, by means of a simple relay system, enables the angular position of the digitiser to be displayed in digits of the familiar decimal system.

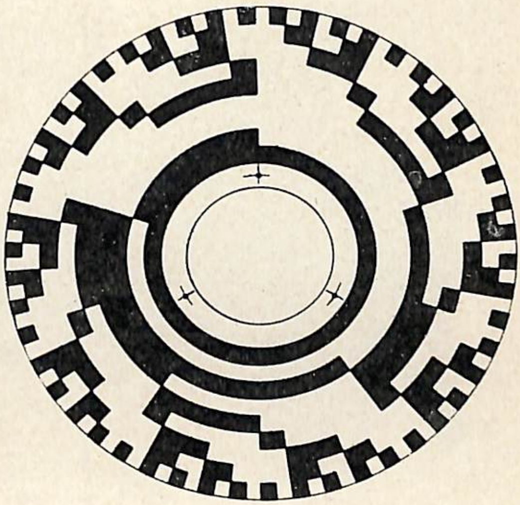

Fig. 21. Example of a Hilger & Watts Binary Coded Scale for Circular Division

In Fig. 22 is shown a simple machine table *C*, which is arranged for longitudinal traverse by means of a leadscrew that can be operated by the handhweel *D*. At the rear of the table is attached the rack *B*, and this rotates the digitisers *A* by means of a pinion. The first digitiser gives a reading up to 9·999 in., and the two digitisers combined provide for a total traverse of 249·999 in. by steps of 0·001 in. The combined rack and pinion used gives an accuracy of 0·001 in. per foot. This system is specifically intended for application to large machine tools, for which the accuracy indicated is sufficient, and enables the scales for the various movements to be centralized in such a position that they are readily observed by the operator.

The two digitisers are so geared and wired together that back-lash is avoided. They are of the optical type, the pick-off being obtained by minute multiple Schwarz photo-conductive cells, and the illuminating system for these cells consists of two standard projector bulbs. No

accuracy is required as regards positioning, and if a bulb fails it can be replaced in a few minutes.

Accurately made rack for the system is produced in sections which, for any particular application, are butted together to obtain the required length, in a manner similar to that adopted for long measuring scales fitted to machine tools. The mating pinion is cut on an accurate circumference, so that the linear movement of the rack is accurately converted into angular displacement which is measured by the digitiser. A close up view of the digitisers, pinion and rack is given in Fig. 23, where the reference letters are the same as those used for Fig. 22. In the complete arrangement, the rack is totally protected by a nylon band to prevent swarf or oil from fouling the teeth and causing damage. The pinion is spring-loaded against the rack to avoid back-lash.

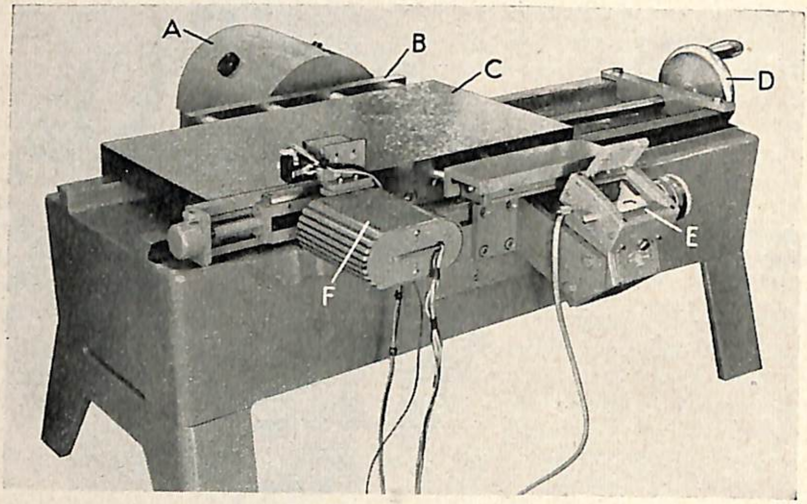

Fig. 22. Machine Bed and Table arranged for Demonstrating the Application of the Digitiser, and the Photo-electric Microscope for Precise Positioning Control. The Projector Unit at *E* is for Demonstration Purposes Only

Since the rack is attached to the machine slide, leadscrew errors are of no consequence, an advantage which this system shares with the machine-tool projector and Photoscope type of position indicator.

The zero of measurement may be shifted to any position within the range of operation. Thus all machining dimensions can be related to a given face of the component as datum, a useful feature when machining castings. Provision is made for reversal of the reading and indicating system, so that movement away from the zero in either direction will give a direct reading of the displacement.

A continuous display of the position of the machine-tool element is provided on a panel such as that shown in Fig. 24. This panel consists of columns of numbers each of which may be illuminated by

a small lamp, and switching is effected by the relays of the decoding system. Instead of the multi-row method of display, a more compact arrangement has been developed by Hilger & Watts, Ltd. A pack of ten transparent plates is provided, each engraved with one of the digits 0 to 9. Each plate is illuminated through its edge by a separate lamp, so that any figure may be illuminated and thus made visible through the superimposed plates.

Since the digitiser provides a direct reading of position, it is claimed that the system cannot be affected by miscounts, nor is a recounting procedure necessary after a shut-down or electrical failure. By the introduction of servo-drive and -control, the system can be made completely automatic.

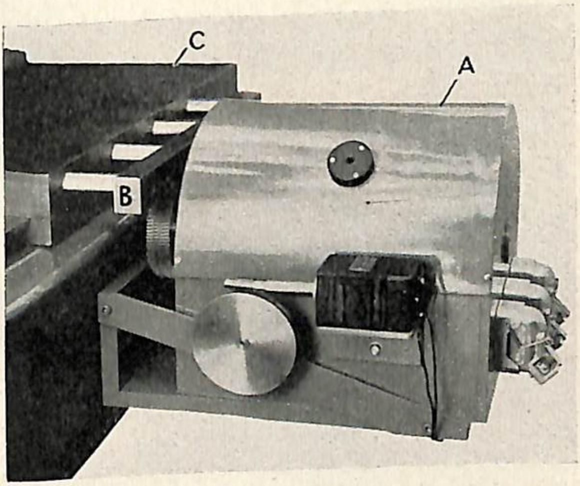

Fig. 23. Close-up View of the Digitisers, and the Operating Rack and Pinion

A high speed of travel can be employed, if required. At high speeds, the channels representing increments of 0·001, 0·01, and 0·1 in. will change so rapidly that it will not be possible to read them. The coarser channels, with their comparatively slow rate of change, will, however, be legible. By arranging for the system to slow down automatically as a required dimension is approached, the final position may be easily read.

Hilger & Watts Photo-electric Microscope System.—The demonstration set-up shown in Fig. 22 incorporates another system of positioning control, which is intended for use when a number of components has to be made accurately to the same dimensions, with manual operation of the traverses. This system is based on the use of a photo-electric microscope which is shown at *F*. The method of operation will be apparent from Fig. 25. The photo-electric microscope is used in conjunction with a scale carrying fine transverse lines each representing

one of the dimensions on the required workpiece. This scale is attached to the saddle of the machine and is directly viewed by the microscope. In addition, there is provided, at *G*, what is termed the coarse scale. This scale is drilled and provided with small insulating inserts in a binary-code arrangement, a group of such inserts corresponding to each fine scale graduation.

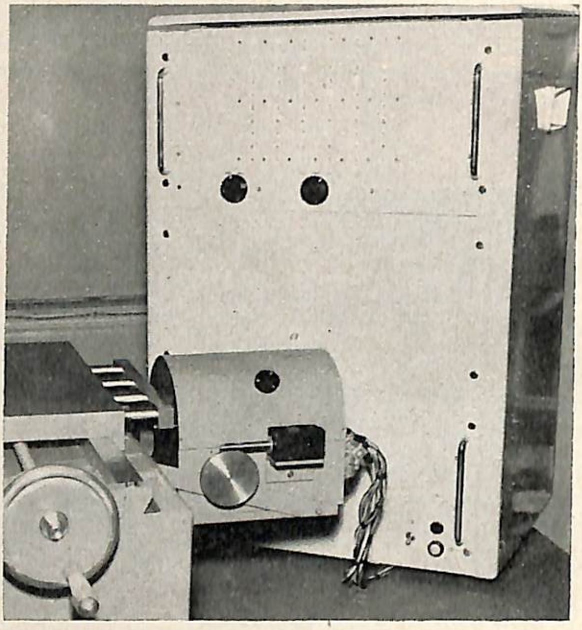

Fig. 24. Block System for Numerical Display for the Dimension Signalled by the Digitiser

To the bed of the machine is attached the detecting head *H*, which operates in conjunction with the coarse scale *G*. As one of the graduated dimensions is approached, metal sensing contacts projecting from the lower face of the head *H* engage the insulating inserts, and certain relay circuits are thus interrupted. A warning signal is thus operated and a number is displayed which identifies the particular graduation and dimension.

The application of this system to the longitudinal and transverse motions of a lathe is illustrated in Fig. 26. Here two photo-electric microscopes or Photoscopes *F* are provided, one for each motion. The Photoscope provides illumination of the engraved line, and the reflected light is directed internally on to a pair of cadmium-selenide cells. The outputs from the two cells operate miniature relays to give warning light indications on a meter dial, such as those at *K*, when the

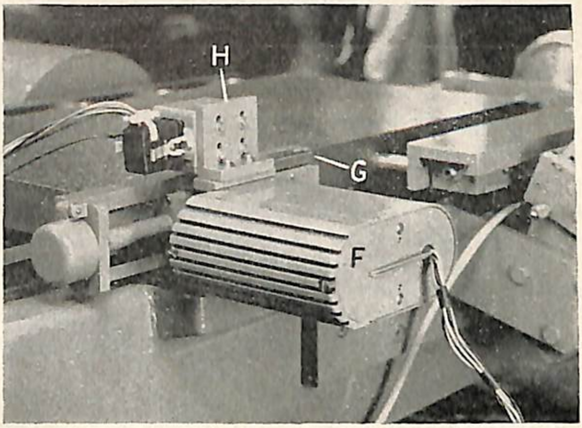

Fig. 25. The Photo-electric Microscope Used for Controlling the Machining Dimension

position error of the microscope is about 0·0002 in., and to give a direct meter indication by needle when the error is smaller. When the needle is at the centre zero of the scale, the required position has been attained to an accuracy of 0·00001 in.

To provide an allowance for subsequent finish-machining, each Photoscope is provided internally with a tilting refractor block which

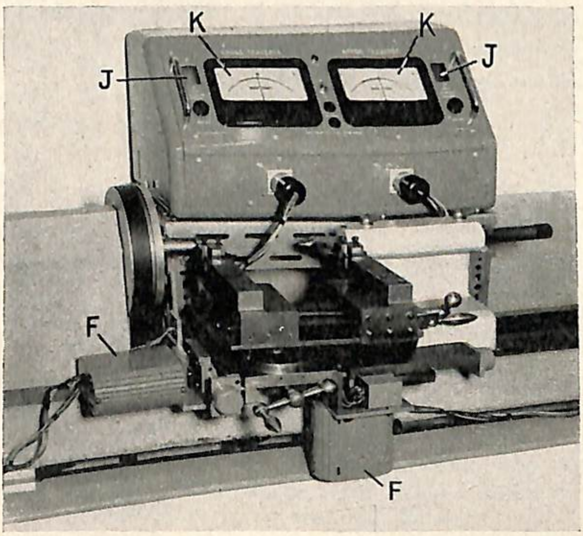

Fig. 26. Application of Two Photo-electric Microscopes to the Longitudinal and Cross Motions of a Lathe

can be set to give an effective lead to the detecting beam of light of about 0·005 in.

The approach warning lights are built around each of the meter faces *K* on the control panel. The meter itself is used only for the final indication if accuracies closer than 0·0002 in. are required. One half of the meter is used in one direction of travel and the other half for the opposite direction. The identification number appears at *J*.

A typical operating sequence is as follows:

Roughing Cut. (1) Switch to "coarse" on the Photoscope; (2) Traverse the machine until the white warning lights appear together with the identification number (within 0·030 to 0·050 in. of finished size); (3) If this is not the desired line, traverse on; (4) If it is the desired line, continue roughing until the green light appears (within 0·005 in. of finished size).

Finishing Cut. (5) Switch to "fine" on Photoscope; (6) Watch for the green light (0·005 in.) and slow down; (7) When the red light joins the green (0·0002 in.) an audible signal is given; (8) If greater accuracy is required, watch the meter, each division of which represents approx. 0·00001 in.

The Photoscope with its control panel is complete in itself, and can often be arranged to fit existing machines. Machine motion can be either manual or by power drive. When the latter is used, an automatic switch can be arranged to switch off the drive when the red and green lights appear, by the introduction of a contactor. Automatic cycling from one line to another can be simply effected by relay-switching circuits.

For accuracies closer than 0·0005 in. the conventional Watts machine tool scale is necessary, but for lower accuracies of, say, 0·001 in., an ordinary scribed metal scale can be employed, which can be made in the tool room.

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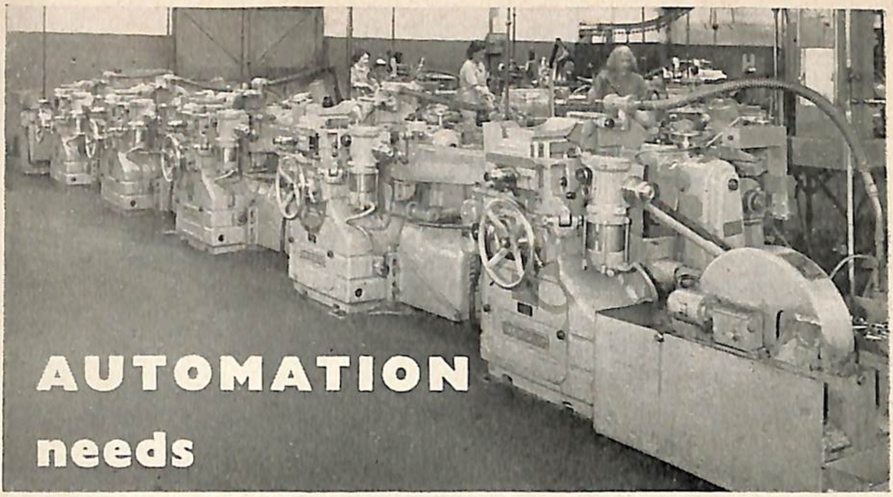

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